

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**DEVELOPMENT of SALIENT-POLE SYNCHRONOUS MACHINES by USING
FRACTIONAL SLOT CONCENTRATED WINDING TECHNIQUE &
ADDITIONAL PERMANENT MAGNETS**

M.Sc. THESIS

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Department of Electrical Engineering

Electrical Engineering Programme

JUNE 2012

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**ÇIKIK KUTUPKU SENKRON MAKİNALARIN KESİRLİ OLUKLU
KONSANTRE SARGI TEKNİĞİ ve İLAVE KALICI MIKNATISLAR
KULLANILARAK GELİŞTİRİLMESİ**

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To my family and friends

I could not have done it without all of you

FOREWORD

I would like to express my gratitude to my advisor, Ass. Prof. Dr. Güven K  m  rg  z for her generous support, professional and skillful guidance, patience, everlasting helpful attitude and for allowing me a high degree of freedom in my research activities over all these years. It has been a great experience working with her. I learn a lot and gained lot of experience.

May 2012

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ABBREVIATIONS

1D	: One Dimensional
2D	: Two Dimensional
15Q8P	: 15 slots-8 poles
69Q8P	: 69 slots-8 poles
AC	: Alternatif Current
Alnico	: Aliminyum-Nickel-Cobalt
aPM-FSCW	: Additional Permanent Magnet Fractional Slot Concentrated Winding
BDCM	: Brushless Direct Current Machine
BH_{max}	: Maximum Energy Product
CD	: Compact Disc
CSDW	: Conventional Slot Distributed Winding
CPSR	: Constant Power Speed Ratio
DC	: Direct Current
DESM	: Double Excited Synchronous Machine
DL	: Double-Layer
DSPM	: Double Salient Permanent Magnet
DVD	: Digital Versatile Disc
EMF	: Electro Motive Force
FE	: Finite Element
FEM	: Finite Element Method
Fig	: Figure
FSCW	: Fractional Slot Concentrated Winding
GCD	: Greatest-Common-Divisor
HDD	: Hard Disc Driver
IPM	: Interior Permanent Magnet
Ind	: Inductive
Inf	: Infinitive
LCM	: The Lowest-Common-Multiple
MMF	: Magneto Motive Force
N	: North
NdFeB	: Neodymium-Iron-Boron
PM	: Permanent Magnet
PMSM	: Permanent Magnet Synchronous Machine
S	: South
SL	: Single-Layer
SmCo	: Samarium-Cobalt
SPSG	: Saline-Pole Synchronous Generator
SPM	: Surface Permanent Magnet
THD	: Total Harmonic Distortion
Wye	: Star Connection

TURKISH ABBREVIATIONS

KM	: Kalıcı Mıknatıs
ÇKSM	: Çıkık Kutuplu Senkron Makina
KODS	: Klasik Oluklu Dağıtılmış Sargı
KOKS	: Kesirli Oluklu Konsantre Sargı
eKM-KOKS	: Ek Kalıcı Mıknatıslı Kesirli Oluklu Konsantre Sargı
SEY	: Sonlu Elemanlar Yöntemi

NOMENCLATURE

A_g, A_b, A_m	area of air-gap, rotor pole-body and PM, respectively
A_{cu}, A_{slot}	total copper and slot area, respectively
b_0	slot opening width of the slot
B_b	magnetic field density of the pole body
B_g	average flux density over the air-gap
B_h	h order component of the flux density
B_m	peak flux density
B_r	magnetic induction
BS_0	distance between the stator teeth
BS_2	width of the stator slot
$B_{winding}$	magnetic field of the stator windings
BH_{max}	maximum product of the magnetic induction
$B_{\delta a}$	peak value of the fundamental no-load air-gap flux density
D, d	average diameter and thickness of the sleeve, respectively
D_C, D_P	average diameter of the stator and rotor, respectively
e_h	induced EMF component by the h order flux
e_{ph}	resultant phase EMF
E_a	induced voltage in the armature windings
f	frequency
F	magneto-motive force (MMF)
F_m, F_f	MMFs induced by field windings and PMs respectively
$Fv(r)$	function depend on the radius and the harmonic order
g	air-gap length
$g^{-1}(\varphi, \theta)$	inverse air-gap function (geometric form of the rotor)
h	harmonic order
H_b	ole body magnetic field intensity
H_d	magnetic field strength
HS_0	thickness of the stator teeth
HS_2	height of the stator slot
i_a	peak value of the phase “a” current
I_a	terminal current
I_{dn}, I_{qn}	normalized d- and q-axis currents, respectively
I_{ph}, I_L, I_f	phase, field and line current, respectively
I_R	rated current of the machine
I_x	characteristic current of the machine
$K_{cu-fill}$	copper slot fill factor
K_B, K_W	bearing and external shape parameters, respectively
k_{ca}	Carter’s coefficient
k_{dh}	distribution factor with h order harmonic for FSCW machine

$k_{dh(c)}$	distribution factor with h order harmonic for CSDW machine
k_{dp}	winding factor without skewing factor
k_n, k_c, k_e	hysteresis, classical eddy-current and excessive loss coefficients, respectively
k_{ph}	pitching factor with h order harmonic
k_R	skin effect factor for the resistance
k_{swh}	skewing factor
k_{s0}	slot opening factor
k_{wh}	winding factor including h order harmonic
l_{av}	average length of a turn
l_b, l_m	length of rotor pole-body and PM, respectively
l_{eff}	effective length
$l_{end,avgr}$	average end turn length of the rotor
$l_{end,avgs}$	average end turn length of the stator
$l_{trn,avgr}$	average turn length of field winding
$l_{trn,avgs}$	average turn length of stator winding
l'	equivalent length of the iron core
L_{ab}	the mutual inductance between any winding “a” and “b”
L_{aa}, L_{bb}	self-inductance of phase “a” and “b”, respectively
L_d, L_q	d -axis and q -axis inductances, respectively
L_{dn}, L_{qn}	normalized d -axis and q -axis inductances, respectively
L_{slot}	slot leakage inductance per slot
m	phase number
M	magnetization of the PM
n'	order of the harmonic with respect to a fundamental whose wave length is equal to the circumference of the rotor
n	speed of the rotating machine
n_{cond}	number of conductors per slot
n_l	number of layers in each slot
N_1, N_2	turn number per coil of FSCW and CSDW machine, respectively
N_a, N_b	turn number of coil “a” and “b”, respectively
N_{ph}	total number of turns of the phase winding
P	number of pole pairs
P_{cuS}, P_{cuR}	stator and rotor copper losses respectively,
P_{in}, P_{out}	input and output power of the machine, respectively
P_{FE}, P_h, P_c, P_e	iron, hysteresis, eddy-current and excess loss, respectively
P_{FW}, P_{ad}, P_S	fractional and windage, additional and stray losses, respectively
q	number of slots per pole per phase
Q	number of slots
R_{AC}	resistance of the stator winding carrying AC per phase
R_R	resistance of the filed winding carrying DC
R_s	outer radius of the stator
S_c	cross-sectional area of the conductor
T	period
V_a	armature terminal voltage
V_{dn}, V_{qn}	normalized d - and q -axis voltages, respectively
V_L	line-line voltage

w_A, w_B	winding function of phase “a” and “b”, respectively
W_f	field winding width

Greek Symbols

α	axis of the phase winding
β	denominator of the fraction that fixes the number of the q value
γ	skew angle which is the angle between the first lamination's slot and its corresponding slot in the last lamination along the axial direction
$\Delta\phi_{fs}$	increase in the armature
η	efficiency
θ	current angle
λ	inverse gap function phase shift with respect to the selected reference axis on the stator
Λ_s	specific slot permeance
μ_0	relative permeability of the air
μ_b	relative permeability of the rotor pole-body core material
μ_m	relative permeability of the PM
μ_r	permeability of the conductor
ξ	saliency ratio
ρ	resistivity of the conductor
σ	specific conductivity of the conductor
T	period
τ_c	stator coil pitch in electrical degree
τ_p	pole pitch in mechanical degree
τ_{pa}	pole pitch in mechanical degrees belong to phase “a”
ϕ_a	Magnetic flux created by I_a
ϕ_s	total armature flux flowing towards to stator
ϕ_{fr}, ϕ_{fs}	field winding fluxes which enter into the rotor and stator respectively
ϕ_m, ϕ_f	total PM and field winding fluxes respectively
ϕ_{mr}, ϕ_{ms}	PM fluxes which enter into the rotor and stator respectively
φ	stator reference axis
Ψ	magnet flux linkage
Ψ_1, Ψ_2	flux linkage of the FSCW and CSDW machine, respectively
Ψ_h	magnetic flux of the h order harmonic
Ψ_n	normalized magnet flux linkage
Ψ_m	peak value of magnet flux linkage
ω	machine electrical speed in radian
ω_n	normalized angular speed of the rotor in radian
ω_r	angular speed of the rotor in radian
$\mathcal{R}_b, \mathcal{R}_m, \mathcal{R}_g$	rotor pole-body, PM, and air-gap reluctances respectively

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DEVELOPMENT of SALIENT-POLE SYNCHRONOUS MACHINES by USING FRACTIONAL SLOT CONCENTRATED WINDING TECHNIQUE & ADDITIONAL PERMANENT MAGNETS

SUMMARY

Considering that the natural sources of the earth are limited, it is necessary to produce economical electrical machines with a high efficiency through a better design and a proper selection of materials. Now, permanent magnets have a high-energy product ($BH_{\max}$) with suitable magnetic and physical properties for applications in electrical machines. In addition to this, use of fractional slot concentrated winding (FSCW) topology in PM machines is gaining importance day by day because of its significant properties. This thesis considers a detailed study about how an electrical engineer could take modern permanent magnets (PMs) and FSCW technique into account when designing an electrical machine.

The PM synchronous machines with fractional slot and concentrated winding configuration have been steadily gaining traction in various applications in recent times. This is mainly driven by several advantages offered by this configuration such as high-torque density, outstanding efficiency, and easy and low-cost fabrication. By implementing the FSCW technique to a PM machine, high slot fill factor and short end turns when coupled with segmented stator structures, low cogging torque, good flux-weakening capability, decreasing in the weight, simple structure, higher efficiency, and higher permeability of the iron cores may be obtained. Same method can be implemented the salient-pole synchronous generators (SPSG) to be able to achieve the same developments. The main focus of this thesis is dedicated to the investigation of three kinds of topologies including conventional slot distributed winding (CSDW) SPSG, FSCW SPSG and additional PM FSCW (aPM-FSCW) SPSG specifically suited for power plants.

This thesis analyses the characteristics of a concentrated two-layer winding, each coil of which is wound around one tooth and which has a number of slots per pole and per phase less than one ($q < 1$). Compared to the integer slot winding, the fractional winding ($q < 1$) has shorter end windings and this, thereby, makes space as well as manufacturing cost saving possible and provides low copper losses.

Implementation of FSCW technique to large SPSGs and development of the generators by using additional PMs placed between the rotor pole-shoes to prevent the saturation of the pole bodies is presented in this thesis. Compared to the conventional synchronous generators, FSCW technique makes it possible to increase the machine inductance in order to achieve lighter, cheaper and high-efficiency SPSGs with more simple structure without reducing the output power. To overcome saturation of the rotor pole-body problem which is well-known in the SPSGs and to achieve more compact, lighter and cheaper (if PM prices are reasonable) generators without decreasing the output power, designed FSCW SPSG has been developed by inserting additional PMs between the rotor-pole shoes. Nevertheless, the PMs are not

used for the field excitation. They are mainly used for the reduction of magnetic saturation at the rotor-pole bodies. However, as a natural result of the position of the PMs placed between the pole-shoes, they do not only reduce the magnetic saturation in the pole bodies but also increase the terminal voltage and also output power.

As an example to implementation of FSCW technique to large SPSGs, a two-layer per slot 2.4 MVA, 15 stator slots, 8 poles, 6.6kV/50Hz SPSG with FSCWs is designed and it is developed with placing additional PMs between rotor pole-shoes to provide the same output power. The winding factor and the winding harmonic components, which are very important to obtain the terminal voltage, are calculated. The benefits attainable from a machine with concentrated windings are considered. The finite element method (FEM) is used to solve the main values of the generators. The waveform of the induced voltage, load current, air-gap flux density, flux linkages, harmonics order of the induced voltage and etc. are plotted after required calculations on FEM program.

Furthermore, a 2D FEM model is developed to analyze and optimize the electromagnetic performance of the designed machines in this thesis. The machines are modeled not only by FEM but also by a simple nonlinear magnetic circuit in order to express the effects of PMs by simple theoretical expressions. To be able to examine the effect of the additional PMs between the pole shoes, the Frozen Permeability Method is used. The rotor and the stator flux components produced by PMs are computed by linear FEM with frozen permeability in an additional PM-FSCW (aPM-FSCW) generator. Detailed comparisons of the performance characteristics of the designed machine CSDW, FSCW and its developed model machine (aPM-FSCW) are presented that include important issues such as the waveform of the induced voltage at full-load, weight and the cost of the machines, all machine losses and saturation status of the iron cores. Guidelines are developed to help machine designers faced with reducing the saturation of the synchronous generator poles without reducing the efficiency and optimal design of the machine. Also in this study, the magnetic and mechanical properties of synchronous machines are analyzed. The results from 2D FEM and the comparisons have validated that the proposed and developed models are a compact and efficient generators with very simple structures. Furthermore, the price guidepost of the modern PMs, which indicates that there will be a large demand for magnets unless alternative technologies prevail, has been shown as this thesis.

ÇIKIK KUTUPKU SENKRON MAKİNALARIN KESİRLİ OLUKLU KONSANTRE SARGI TEKNİĞİ ve İLAVE KALICI MİKNATISLAR KULLANILARAK GELİŞTİRİLMESİ

ÖZET

İnsan oğlunun elektrik enerjisine olan ihtiyacı, her geçen gün biraz daha artmaktadır. Bunun sonucu olarak, yeni elektrik enerjisi santralleri kurulmalı ya da kurulu olan enerji santrallerinin verimi ve kapasiteleri arttırılmalıdır. Bir elektrik enerji santralindeki en önemli ünitelerden birisi, hareket enerjisini elektrik enerjisine çeviren generatörlerdir. Bu yüzden, kompakt, verimli ve daha ucuz elektrik makinalarından biri olan Kalıcı Mıknatıslı (KM) makinalara olan talep giderek artmıştır. Ancak, son yıllarda KM'ların fiyatlarında çok yüksek ölçüde artış olması sonucu, klasik sargılı makina tasarımları tekrar önem kazanmaya başlamıştır. Elektrik enerjisi üretim santrallerinden, yüksek güç yoğunluğu gerektiren motor uygulamalarına kadar bir çok alanda Çıkık Kutuplu Senkron Makinalar (ÇKSM) uzun yıllardır yaygın olarak kullanılmaktadır. Bu makinalarda çıkış gücünü, rotordaki uyartım sargılarında endüklenen manyeto motor kuvveti belirler ve bu kuvvet uyartım sargılarının kesit alanı ile doğru orantılıdır. Genellikle, makinanın rotor kutup gövdeleri manyetik doymaya gider çünkü, makina boyutlarını arttırmadan maksimum manyeto motor kuvvetini elde edebilmek için rotor kutup gövdelerinin boyutları daha fazla uyartım sargısı sarılabilmesi için azaltılmalıdır.

Manyetik doyma uyartım sargılarının kesit alanları genişletilerek (daha fazla sarım sayısı ile) azaltılabilir. Ancak, bu durumda makina boyutlarını ve dolayısı ile ağırlığını arttırmamak için rotor gövdelerinin boyutları azaltılmalıdır ki bu da rotor kutup gövdelerindeki manyetik akı yoğunluğunun artmasına sebep olur. Sonuç olarak, endüklenen manyeto motor kuvveti artsa bile, generatörün maksimum çıkış gücü artmaz ya da makina boyutlarında bir azalma olmaz. Bu durumda, makina verimi azalır ve/veya toplam makina ağırlığı artar.

Manyetik doyma generatörün çıkış gerilimini sınırlar ve gerekli olan çıkış gerilimini sağlayabilmek için daha fazla uyartım gücünün kullanılmasını zorunlu kılar. Bu da rotorda ilave kayıplara neden olmakla beraber; makinanın veriminin azalmasına, toplam ağırlığının artmasına sebep olur. Bu tasarım sınırlamasının üstesinden gelebilmek; makinanın verimini arttırıp, ağırlığını azaltmak için Kesirli Oluklu Konsantre Sargı (KOKS) tekniği ÇKSM'lerde kullanılabilir. Ayrıca, hem kutupların doymasını önleyen hem de çıkış geriliminin artmasını sağlayan, birbirine komşu olan rotor kutup ayaklarının aralarına KM'lar yerleştirilerek KOKS tekniği ile tasarlanmış makinanın geliştirilmesi sağlanabilir.

Dünyadaki doğal kaynakların sınırlı olduğu göz önüne alındığında, yüksek verimli ve ekonomik elektrik makinalarının, doğru malzeme seçimi ve iyi bir tasarımla üretilmesi gerekmektedir. Uygun manyetik ve fiziksel özelliklerle beraber yüksek enerji yoğunluğuna (BH_{max}) sahip olan KM'lar günümüzde elektrik makinalarının uygulamalarında yaygın bir şekilde kullanılmaktadır. Ayrıca, KOKS topolojisinin

KM makinalarda kullanımı, bu tekniğin önemli özelliklerinden dolayı gün geçtikçe artmaktadır. Bu tezde, bir elektrik mühendisinin elektrik makinası tasarımında modern KM'ları ve KOKS tekniğini nasıl tasarıma katacağı ayrıntılı bir şekilde açıklanmıştır.

Son zamanlarda, kesirli oluk ve konsantre sargılı konfigürasyonlara sahip olan KM'lı senkron makinalar, çeşitli uygulama alanlarında giderek önem kazanmaktadır. Bunun temel sebebi ise; bu konfigürasyonun yüksek moment yoğunluğu, yüksek verim, kolay ve ucuz fabrikasyon gibi çeşitli avantajları elektrik makinalarına kazandırmasıdır. Bir KM'lı senkron makinanın üretiminde KOKS tekniği kullanıldığı zaman, yüksek oluk doldurma faktörü, segmentli stator yapılarıyla birleşir ve sonuçta; kısa sargı başı uzunlukları, düşük vurutu momenti, iyi alan zayıflatma kapasitesi, toplam ağırlıkta azalma, basit yapı, yüksek verim ve yüksek geçirgenlikli demir nüveli makinalar elde edilebilir. Aynı teknik, aynı üstün gelişmeleri elde etmek için ÇKSM da uygulanabilir. Bu tezin ana odak noktası özellikle güç santralleri için tasarlanan Klasik Oluklu Dağıtılmış Sargılı (KODS) çıkık kutuplu senkron generatör (ÇKSG), KOKS ÇKSG ve ek KM SPSM (eKM-KOKS)'lerin incelenmesi üzerinedir.

Bu tezde, her biri bir stator dişi etrafına sarılmış, kutup başına oluk ve faz sayısı birden küçük olan ($q < 1$) çift tabakalı konsantre sargıların karakteristiklerinin analizleri incelenmiştir. Kesirli oluklu sargılar ($q < 1$ için), tam adımlı (oluklu) sargılarla kıyaslanınca daha kısa bitiş sargılarına sahiptirler ve bu da makinanın bakır kayıplarının daha az olmasına ve daha ucuz imalat edilmesine imkan sağlar.

KOKS tekniğinin yüksek güçlü ÇKSG'lere uygulanması ve bu generatörlerin rotor kutup gövdelerinin doymaya gitmesini önleyen, rotor kutup başlarının arasına ek mıknatıslar yerleştirilmesiyle bu generatörlerin geliştirilmesi sunulmuştur. KOKS tekniği makinanın endüktansının artırarak, makinanın çıkış gücünü azaltmadan klasik senkron generatörlere (KODS) göre daha basit yapılı, daha hafif, ucuz ve yüksek verimli ÇKSG'lerinin tasarımını mümkün kılar. ÇKSG'lerde sık rastlanılan rotor kutup gövdelerinin doyması problemini çözmek ve çıkış gücünü düşürmeden daha kompakt, hafif ve ucuz (eğer KM fiyatları uygunsa) generatörler tasarlayabilmek için tasarlanan KOKS ÇKSG'nin bir birine komşu olan rotor kutup başlarının aralarına KM'lar yerleştirilerek makinanın geliştirilmesi sağlanmıştır. Ancak buradaki PM'lerin görevi makinanın uyarımını sağlamak değildir. Bu mıknatıslar, özellikle rotor kutup gövdelerinde oluşan manyetik doymayı önlemek için kullanılmıştır. Ancak, kutup başı aralarına yerleştirilen bu mıknatısların yönlerinin (polarizasyonlarının) doğal sonucu olarak, sadece kutup gövdelerindeki manyetik doyma azalmakla kalmamış, aynı zamanda makinanın çıkış gerilimi ve gücü de artmıştır.

KOKS tekniğinin ÇKSM'lere uygulanmasına bir örnek olarak, oluk başına çift-tabakalı 2.4 MVA, 15 oluk, 8 kutuplu, 6.6kV/50Hz KOKS'lı ÇKSG tasarlanmış ve aynı çıkış gücünü elde edecek şekilde, rotor kutup başları aralarına ek KM'lar yerleştirilerek bu makinanın geliştirilmesi sağlanmıştır. Çıkış geriliminin elde edilmesinde büyük rol oynayan sargı faktörü ve sargı harmonik bileşenleri hesaplanmıştır. Konsantre sargılara sahip bir makinadan erişilebilecek avantajlar gözönüne alınmıştır. Tasarlanan generatörlerin temel değerlerinin hesaplanmasında sonlu elemanlar yönetimi (SEY) kullanılmıştır. Endüklenen gerilim, yük akımı, hava aralığı manyetik akı yoğunluğu, kaçak akıların dalga şekilleri, endüklenen gerilimin

harmonik dereceleri ve bunun gibi makina çıkış büyüklükleri, SEY programında gerekli hesaplamalar yapılarak incelenmiştir.

Bunlara ek olarak, bu tezde iki boyutlu (2D) SEY modeli, tasarlanan makinaların elektromanyetik performansını analiz ve optimize etmek için geliştirilmiştir. Makinalar sadece SEY kullanılarak değil, analizi basit teorik ifadelerle ifade etmek için basit lineer olmayan manyetik devre ile de modellenmiştir. Kutup başı aralarına sonradan eklenen mıknatısların etkisini gözlemlemek için "Frozen Permeability" yöntemi kullanılabilir. Bir ek KM'li (eKM-KOKS) generatördeki, KM'ler tarafından üretilen rotor ve statordaki manyetik akı bilşenleri SEY ile "Frozen Permeability" yöntemi birleştirilerek hesaplanabilir. Tasarımı yapılan KODS, KOKS ve KOKS'un geliştirilmiş modeli olan eKM-KOKS generatörlerinin performans karakteristiklerini yansıtan; tam yükteki endüklenen gerilimin dalga şekli, ağırlıkları, maliyetleri, toplam makina kayıpları ve demir nüvelerin doyum durumları gibi önemli konular ayrıntılı karşılaştırılmalarla sunulmuştur. Bu tez, senkron generatörlerin verimini düşürmeden ve makinanın optimal tasarımını engellemeden, generatör kutuplarının doyumunun azaltılması sorununu çözmeye çalışan makina tasarımcılarına yol gösterecek şekilde hazırlanmıştır. Ayrıca bu tezde, senkron makinaların manyetik ve mekaniksel özellikleri analiz edilmiştir. 2D SEY analiz sonuçları ve kıyaslamalar sayesinde, tasarlanan ve geliştirilen modellerin basit yapıda, yüksek verimli ve kompakt generetörler olduğu doğrulanmıştır. Bunlara ek olarak, KM talep ve fiyatları bu tezde ayrıca incelenmiştir. Alternatif teknolojiler geliştirilmediği sürece modern KM'lara olan ilginin göz ardı edilemeyecek şekilde artacağı varsayımı verilen KM fiyat tabloları ile desteklenmiştir.

Bu tezin temel amacı, bir ÇKSM'nin KOKS tekniği kullanılarak, çıkış gücü düşürülmeden, ağırlığını ve maliyetini azaltılıp, veriminin nasıl arttırılacağı hakkında temel bilgileri vermektir. Çok daha yüksek oluk doldurma faktörüne sahip olan konsantre sargılar kullanılarak, herbir stator dişine bir fazın bir faz bobini gelecek şekilde tasarım yapıldığında, hem üst üste kesişen ve karmaşık olan klasik sargıların çok daha basit bir sargı topolojisine nasıl dönüştürüleceği ve kesişmeyen, kısa bitiş sargıları sayesinde nasıl verimin arttırılacağını basitçe açıklamak da bu tezin amaçları arasındadır. Tezin bunlardan farklı olarak diğer bir amacı da, tasarımı yapılmış bir KOKS ÇKSG'nin, birbirine komşu olan kutup ayaklarının arasına KM'lar yerleştirilerek makinanın geliştirilmesinin nasıl yapılacağını açık bir şekilde sunmaktır. Bu manyetik doymayı azaltma yöntemini sayesinde, terminal gerilimi, çıkış gücü, ve yüklenme kapasitesi gibi çıkış karakteristikleri geliştirilebileceği gibi, çıkış gücünü ve makina verimini azaltmadan makinanın boyutları küçültülebilir. Bu çalışmada, klasik sargılı generatörle aynı boyutlardaki bir KOKS generatörün çıkış karakteristiklerinin geliştirilmesi yerine, klasik generator ile aynı çıkış karakteristiklerine sahip ancak çok daha küçük boyutlarda ve ağırlıkta makinaların tasarlanması amaçlanmıştır.

1. INTRODUCTION

The need for electrical energy of humanity is increasing more and more with each passing day. So, new power plants should be planted or capacity and efficiency of the existing power plants should be increased. The most important unit of a power plant is the generator, which is converted the rotating mechanical power of the turbine into electrical energy. Therefore, demand for more compact, efficiently and cheaper electric machines has grown tremendously during the last decade. Meanwhile, a great progress has been achieved not only in the development of PMs but in the area of electric machine design and power electronics as well. Therefore, PM machines have been drawing more and more attention. However, conventional machines have been starting to draw more attention because of the very high PM prices [1]. In the power-energy production plants (i.e. hydro generators, engine generators, wind generators, and so forth), and in the high-power electric motors grid-supplied or converter-supplied high power electric motors (i.e. steel mill motors), salient-pole synchronous generators (SPSG) have been widely used for decades [2-5]. In these machines, the output power is determined by the magneto motive force (MMF) of the field windings on the rotor and it is proportional to the cross sectional area of the field windings. In most cases, saturation occurs in the pole-bodies because; the rotor pole-bodies should be reduced for maximum MMF to be able to maintain the total machine size [6].

The magnetic saturation can be reduced by enlarging the cross sectional area of field windings. However, the rotor pole-bodies should be reduced in this case in order to maintain the total machine size and this causes an increase in the flux density again. Consequently, the maximum output power of the generator does not increase or the dimensions of the machine do not decrease despite the increase in the magneto motive force. In this case, the efficiency of generator considerably decreases or/and the total weight of the generator increases.

The magnetic saturation limits the armature terminal voltage and requires more excitation power and the additional losses in the damper windings are reduced the

efficiency and increased the total machine weight. To overcome this design limit and to make efficiency higher with lower weight, FSCW technique may be used in SPSG and its output characteristics may be developed by inserting additional PMs between the adjacent rotor-pole shoes.

Recently, a great interest has grown towards PM electrical machines with concentrated coils, thanks to their conspicuous constructional and functional advantages. They are mainly an easier machine manufacture and the development of high torques and electro motive forces (EMFs) at low speed. Since a distributed overlapping winding generally results in a more sinusoidal MMF distribution and EMF waveform, it is used extensively in PM brushless ac machines.

Actually, FSCW topology has been used for flux weakening operations for achieving constant-power speed range in the PM synchronous machines designed for small power applications [7-13]. By implementing the FSCW technique to a PM machine, high slot fill factor and short end turns when coupled with segmented stator structures, low cogging torque, good flux-weakening capability, decreasing in the weight, simple structure, higher efficiency, and higher permeability of the iron cores may be obtained. According to [7], flux-weakening technique is not frequently used in larger electrical machines where efficiency and smooth torque production are more important. But in this thesis, same method was implemented the SPSG to be able to achieve the same developments, developing the winding factor of the machine. Furthermore, additional PMs between the pole-bodies technique used for CSDW SPSG for large and small power applications [14-17]. Additional to these, a number of types of synchronous machines having both field windings and PMs in the field poles have been presented [18-21]. Whereas, other publications neither discuss an attempt to add PMs between the adjacent field pole-shoes for FSCW SPSGs nor reducing the magnetic saturation by FSCW technique so far in the literature.

Principle schemes of the designed machines shown in Fig. 1.1. Concentrated windings refer to windings that encircle a single stator tooth; eliminating any end-winding overlap with other phase windings thus prevents saturation of the poles. The total copper weight and copper losses may be reduced using FSCWs in the stator of the generators.

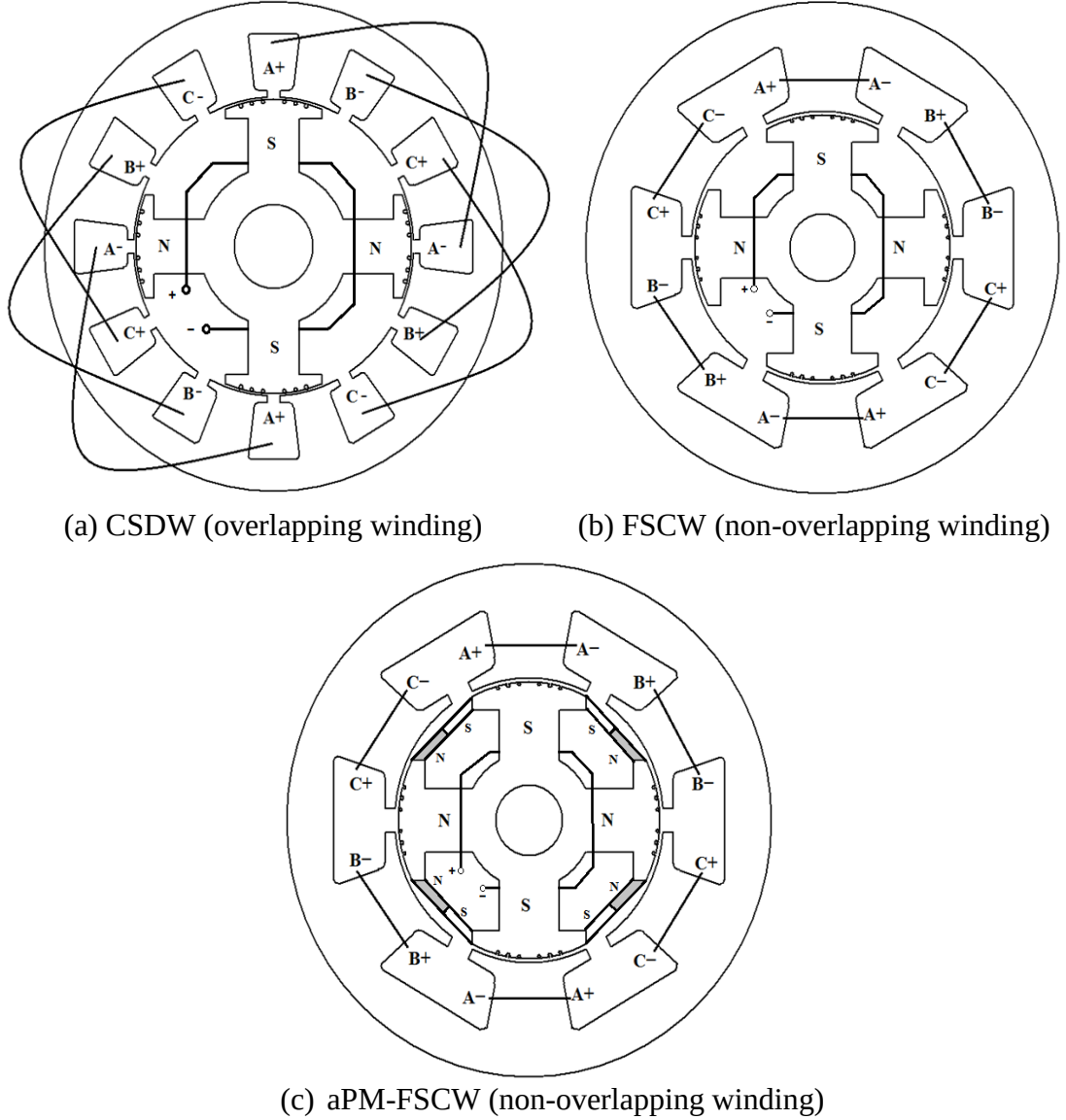


Figure 1.1: Principle schemes of the designed machines; (a) conventional slot distributed winding; (b) fractional slot concentrated winding; (c) fractional slot concentrated winding machine with additional PMs.

The purpose for using PMs is not to provide additional field excitation in the aPM-FSCW machine. They are mainly used for the reduction of magnetic saturation at the rotor-pole bodies. But, they increase the terminal voltage as a natural result of the position of the PMs placed between the pole-shoes. In other words, PMs will provide extra excitation for stator windings. Therefore, as a result of using FSCWs in the stator and PMs in the rotor of the generator, the stator and field copper usage of aPM-FSCW SPSG can be significantly reduced compared to the CSDW and FSCW machine by using only a small amount of PM. Furthermore, the stator copper usage of FSCW SPSG can be reduced eliminating any end-winding overlap compared to the CSDW generator.

In this thesis, the mechanism of reducing magnetic saturation by FSCW technique is investigated by using both the simple nonlinear magnetic circuit and the FEM at first. Simple nonlinear magnetic circuit model which is well known in the literature [22-27] is developed to predict the electromagnetic performance. Then, the development of the designed FSCW machine is made by additional PMs between the pole-bodies and it is investigated by using frozen permeability technique. The frozen permeabilities technique with FEM can be used as a method of apportioning flux-linkage contributions to the phase currents and permanent magnets, and for inductance calculations [28-33]. In addition to these analysis method, an another analytical approach based on a 2D analytical technique for calculating the magnetic field produced by the windings of any 3-phase ac machine is adopted instead of classical 1D analytical techniques including dq, complex vector and ac phasor techniques, due to the large air-gap area of the FSCW SPSG would lead to a significant error in the magnetic field calculation [28].

As an example to implementation of FSCW technique to large SPSGs, a two-layer per slot 2.4 MVA, 15 stator slots, 8 poles, 6.6kV/50Hz SPSG with FSCWs is designed and it is developed with placing additional PMs between rotor pole-shoes to provide the same output power. In the stator of the SPSG, FSCWs are used instead of CSDWs to achieve;

- a) iron cores with high permeability in pole-bodies,
- b) lower weight and cost without reducing the output power,
- c) simple structure,
- d) ability to meet more electrical load.

and aPM-FSCW SPSG was designed to achieve;

- a) increase in relative permeability of the pole-body core,
- b) increase in efficiency,
- c) more reduction in the machine total length, dimensions and also weight.

The characteristics of the proposed machines, such as output, efficiency, harmonics, and active material dimensions with their weights are compared and the effect of the PMs on the performance characteristics of the aPM-FSCW is also investigated.

A design approach for achieving pole iron cores with higher permeability in generator poles reduced copper usage in stator and also total weight of the machine by properly designing the machine's stator windings using FSCWs in the stator is presented. Furthermore, a development procedure including development of the FSCW generator by additional PMs which helps to prevent the saturation and increases the output voltage of the machine is introduced. Using this significant development method it is shown that compact, lighter and higher efficiency generators may be designed without decreasing output power which is same with its conventional model. Additional advantages of the approach have been discussed including magnetic saturation, cogging torque in two-teeth, efficiency, weight and cost. A systematic machine design procedure based on FEM is introduced for achieving this desired performance characteristics. The results of applying this design approach to a two layers per slot 2.4 MVA SPSG is compared and presented. Addition to this, performance characteristics of conventional and FSCW machines are analyzed and machine losses with eddy effect and efficiency are also evaluated.

1.1 Purpose of Thesis

A major objective of this thesis is to provide a clear explanation of how concentrated fractional-slot windings make it possible to achieve lighter, cheaper and high-efficiency SPSGs with more simple structure without reducing the output power by using FSCW technique. Moreover, the other objective of this thesis is to provide to development of FSCW generator to prevent the saturation of the pole bodies inserting additional PMs between the adjacent pole shoes. Using this saturation reduction method, output parameters of the generators such as terminal voltage, output power and loading capacity may be increased or the dimensions of the generator may be decreased without changing the output voltage and power. In this study, it is purposed that the dimensions of the FSCW generator is decreased instead of increasing the output variables to be able to achieve the highest efficiency.

1.2 Literature Review

A survey of the main research work done in the areas relevant those under consideration in this thesis is presented in this part of the thesis. These areas of existing can be globally divided into four main categories. The first area of interest is

flux-weakening and high-speed operation of interior PM (IPM) synchronous machines. The second is flux-weakening and high-speed operation of surface PM (SPM) synchronous machines. The third area of interest is the use of concentrated winding in various machines applications and the last one is synchronous machines having both field windings and PMs in the field poles.

1.2.1 Flux-weakening and high-speed operating of IPM synchronous machines

In the mid-1980s, the suitability of interior permanent magnet motors (IPMs) for field-weakening applications was first investigated by Sneyers et. al. [34] and Jahns [35]. Sebastian and Slemon [36] examined the design of inset (a form of interior) PM motors to optimize the field-weakening performance, but Schiferl and Lipo [37] made the first serious attempt to determine the effect of varying the motor parameters on the field weakening performance. Also they identified and presented the criteria for achieving optimum flux-weakening performance. The normalized motor model to unity rated speed was applied by Adnan et. al. [36,40] to finite-maximum-speed drives. Betz [41] also used a normalized model to analyze synchronous reluctance machines. The maximum torque flux-weakening control of infinite-maximum-speed drives has been thoroughly analyzed by Morimoto et. al. [42]. The operating limits were examined taking demagnetization of the permanent magnets into consideration.

Soong and Miller [43-45] carried out a study that provided a thorough investigation of the high-speed torque production capabilities for the IPM machine parameter space. This study identified all IPM machine parameter combinations that meet the optimum flux-weakening criteria as well as insights into how the drive performance degrades as the machine parameters deviate from the optimum criteria. Jahns [46] presented a methodical description of the impact of the IPM machine parameters on the inverter and machine ratings in order to clarify the dependencies and tradeoffs that are involved in achieving constant-power operation over a wide range of speeds.

Several authors have addressed the issue of dq cross-saturation or cross-coupling. Sneyers et. al. [34] investigated cross-coupling in a low-saliency single-barrier IPM machine. It was suggested that cross-coupling effect is significant and can enhance the power capability at high speeds. This claim was contested by Richter and Neumann [47]. It was shown that for some IPM machines, the effect of cross-coupling disappears at low-flux high-speed operating points. Mecrow and Jack [48]

investigated cross-coupling in radial spoke type IPM designs and showed that it can have a significant effect on the torque production at low speed.

Soong and Miller [45] investigated the effect of stator resistance, magnetic saturation and iron losses on the flux-weakening performance of brushless synchronous AC motor drives. They showed that saturation could significantly reduce the constant power speed ratio (CPSR) of motor drive by increasing the internal maximum torque per current angle. It was also shown that the stator resistance and iron losses do not have much effect on the CPSR however they reduce the output power.

Several authors addressed the issue of designing IPM machines optimized for flux-weakening operation. Fratta et. al. [49] presented a comparison between induction machines, synchronous reluctance machines and IPM machines for spindle drive applications. It was shown that an axially-laminated reluctance motor gives more torque density than the induction motor but nearly requires the same inverter size. By adding a proper quantity of permanent magnets, the inverter size can be significantly reduced. The main conclusion was that the best solution for spindle drives is the use of a distributed anisotropy IPM machine.

Matsuo and Lipo [50] demonstrated that the rotor geometry of the synchronous reluctance machine could be optimized to obtain maximum torque production. The equation that gives the machine maximum power factor in terms of saliency ratio has been derived.

Eastham et. al. [51] presented a novel IPM machine that uses radial quadrature axis flux barriers. The flux barriers modify the q-axis magnetic path while leaving the d-axis path unchanged. At full flux operation, the barriers limit the flux driven by the armature MMF allowing an increase in the current density and hence torque for the same saturation level. Good flux-weakening is possible due to the enhanced armature current loading. A disadvantage of the machine is that the reluctance torque is reduced.

Honda et. al. [52] investigated different magnet and winding configurations for IPM machines design. It was shown that an IPM machine with two layers of magnet produces 10 % more torque than an IPM machine with one layer of magnets for the same current. It was also shown that a standard concentrated winding of 0.5 slot/pole/phase (q) is inferior to distributed windings in terms of production and the

width of the constant power region. Also the saliency ratio is lower in case of concentrated winding and hence the reluctance torque is also lower.

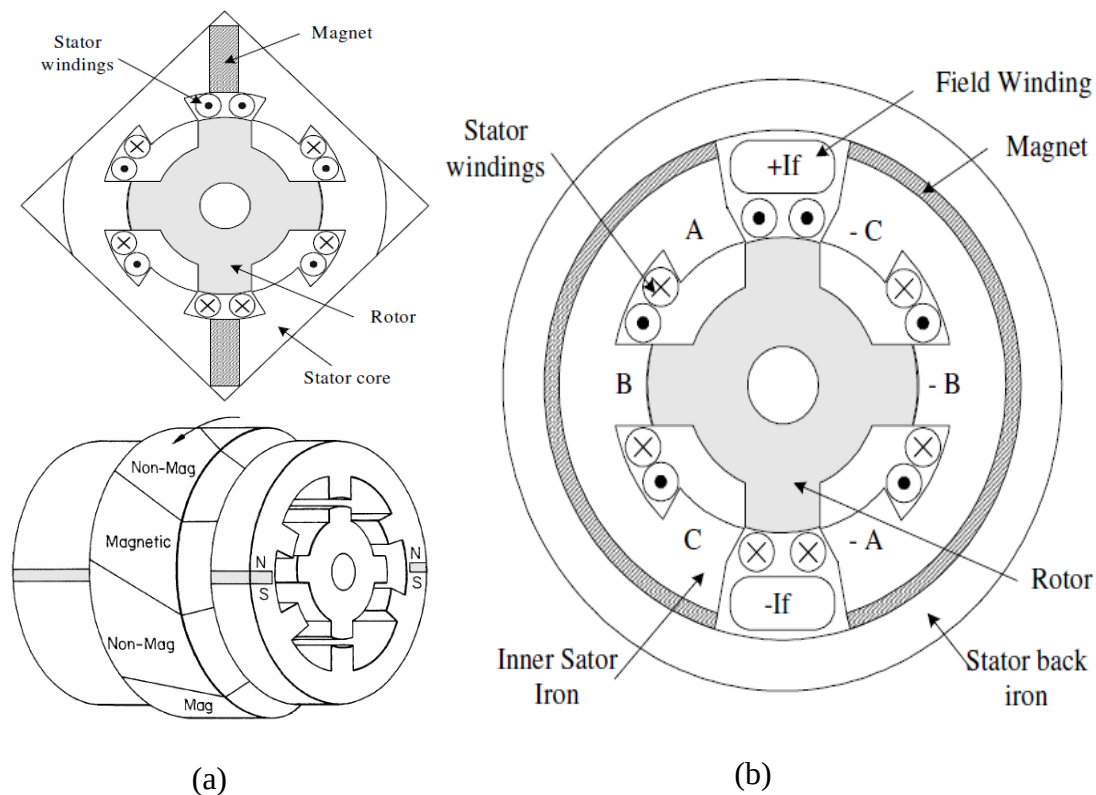


Figure 1.2: Double salient machines; (a) Double Salient IPM machine with flux control [38-40], (b) Double Salient interior magnet machine [41].

Such DSPM machines can be used for adjustable speed drive applications with improved efficiency and power/torque density. It is one of the true field weakening PM machine topologies which was developed at the University of Wisconsin-Madison [38-40] by Lipo and et al. given in Fig. 1.2 (a). One important advantage of the DSPM machine is to utilize the high energy NdFeB magnets. Required air-gap flux can be provided through this small size and small magnet thickness. Another type of DSPM machine is illustrated in Fig. 1.2 (b). In this case, PMs are introduced by using ferrite magnets on the inner surface area of the stator and a circumferential DC field winding is placed in the stator core. Flux boosting or weakening can be achieved simply changing the direction of the current. One important advantage is that the magnet cost is reduced dramatically in this structure [41].

A different DSPM machine configuration suitable for traction application is given in Fig. 1.3 (a). This machine is the inside-out version of the previous DSPM machine. By reversing the location of rotor and stator, air-gap diameter is increased resulting

in increased torque capability. A hybrid electric machine proposed is illustrated in Fig 1.3 (b) [53-55]. The PM machine is formed with a stator and rotor, which is composed of two field magnets. Both field magnets are opposing with the magnet stator pole with a mechanism for varying a phase of magnetic pole. The two rotor concept could be applied to any surface magnet or interior magnet structures. The first field magnets of the rotor is alternately arranged with opposite magnetic poles and the second one has the same structure and is capable of causing relative angular displacement relative to the first one in order to achieve field weakening.

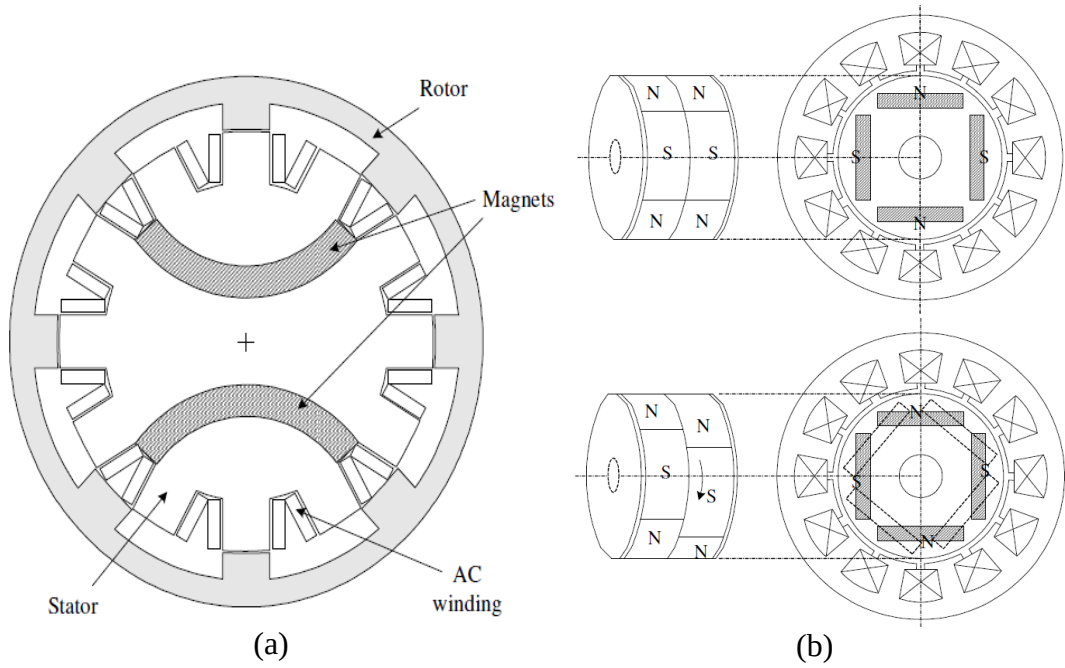


Figure 1.3: Outer rotor double salient machines; (a) Outer rotor double salient IPM machine [42], (b) Dynamo electric machine [53-55].

Profumo et. al. [19] develop one of the axial flux interior machines for flux weakening operation. The machine structure over two poles is displayed in Fig. 1.4 (a). This work deals with the design of a new Axial Flux Interior PM machine with flux weakening capability by the use of soft magnetic materials. An axial flux PM machine which has DC field coils designed by Liange et. al. as Fig. 1.4 (b) [41]. This axial flux machine comprises two stators and one rotor which has permanent magnets and pole portions. The magnets in the rotor generate a first magnetic flux and the consequent rotor poles generate a second magnetic flux. A field coil, which is mounted to the housing and located very close to the rotor, is very effective to vary the second magnetic flux mentioned and therefore the machine provides a controllable output voltage.

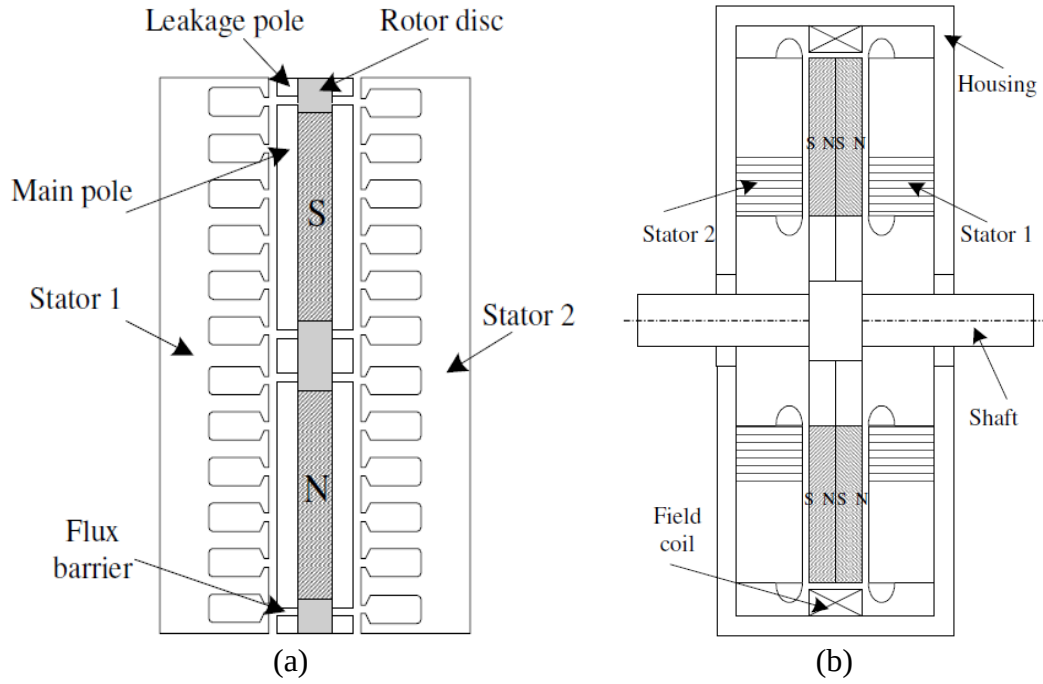


Figure 1.4: Axial flux IPM machines; (a) Axial flux IPM synchronous machine realized with powdered soft magnetic materials, (b) An axial IPM machine with flux control [36].

Another interesting axial flux machine with flux control feature is proposed in [40,56]. This machine uses a field weakening coil to achieve field weakening by directly controlling the magnitude and polarity of a DC current of the field weakening coil. The machine structure and the rotor are displayed in Fig. 1.5.

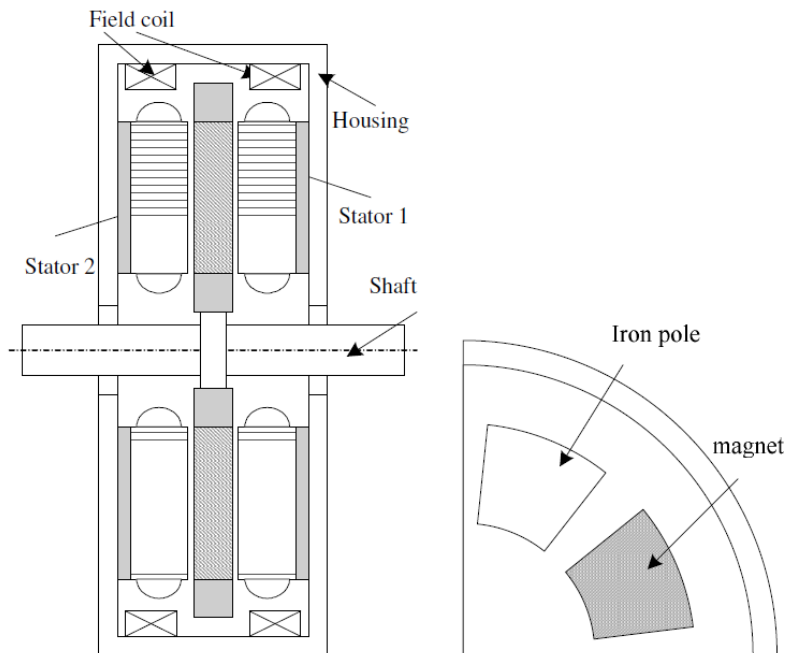


Figure 1.5: An axial flux PM machine with direct control of air-gap flux [40,56].

1.2.2 FSCW theory and various machines applications using concentrated windings

Surface PM synchronous machines have been traditionally considered poor candidates for flux-weakening by many authors [57]. The reason for this is that its characteristic current or the ratio of the magnet flux linkage to the machine inductance is usually several times higher than the rated current of the machine. The machine inductance is low due to the large effective air-gap of the machine. The magnet flux linkage is high since the magnets are the only source of torque. From the machine design point of view, most of the work previously done to improve the flux weakening capability of surface PM machines falls into two categories. The first category focuses on increasing the machine inductance while the second category focuses on reducing the net magnet flux linkage in order to reduce the machine characteristic current.

Cambier et. al. [58] presented a phase advance technique to extend the constant power region of operation of brushless dc machine. Lawler et al. [59-62] highlighted the limitations of this method and showed that if the machine inductance is low, which is the case in surface PM machines, the required current will be excessive.

While other authors have reported on the use of concentrated windings in PM machines [63,64], there has been no previous publication describing specific design techniques for applying such windings to achieve optimal flux weakening conditions in surface PM machines. Cros et. al. [63] qualitatively indicated that fractional slot concentrated windings have the potential the flux-weakening capabilities of surface PM machines. Magnussen et. al. [64] presented a surface PM design using concentrated windings with claim of optimum flux-weakening. Optimum flux-weakening was achieved by adjusting the slot leakage inductance of the surface PM machine designed by Zhu et. al. [65].

Several authors have presented ideas for reducing the net magnet flux linkage. Nipp [66,67] presented an alternative of flux-weakening in surface PM machines by switching the stator windings into different configurations. Caricchi et. al. [68] presented an axial flux PM machine capable of achieving constant power operation over a wide speed range. Zhu [69] presented that Fractional slot PM brushless machines having concentrated non-overlapping windings have high torque density,

high efficiency, low torque ripple, good flux-weakening and fault-tolerance performance.

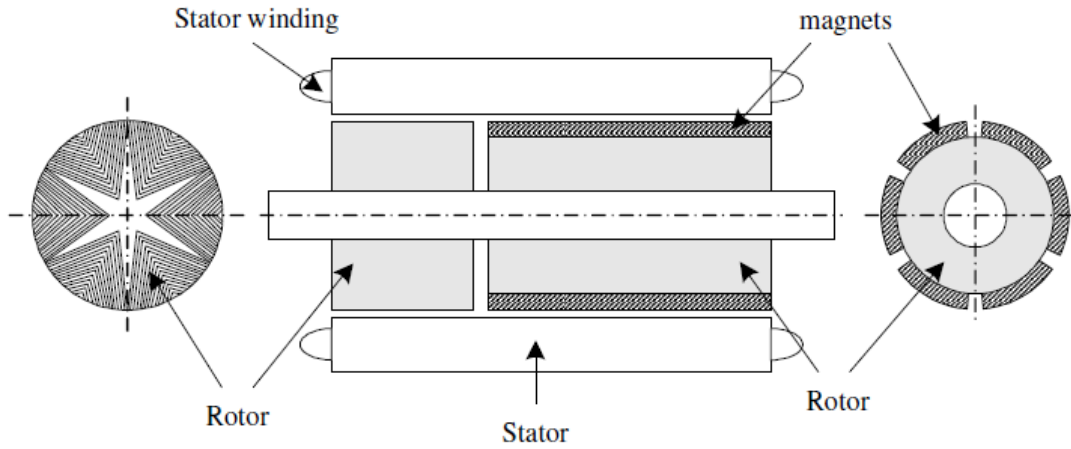


Figure 1.6: Two part rotor synchronous PM machine [70].

A PM machine topology with flux weakening capability given in Fig. 1.6 developed by Chalmers et. al. [70]. In this machine, the rotor structure is composed of two sections, one of which is surface mounted part and the other is axially laminated reluctance section, and they are both connected to the same shaft. The main objective of such a design is that the two rotor sections can be design independently so as to acquire a desired ratio of direct inductance to quarter inductance.

A radial flux PM machine with air-gap flux weakening is designed by Xu as it shown in Fig. 1.7 (a) [57]. This machine has an annular iron mounted on the surface of the magnets. There exist four iron sections and eight flux barriers as seen in the figure. The stator structure is the same as conventional radial flux PM machine. In this structure, the control of air-gap flux is achieved by applying d -axis current, which is not used to lessen the magnet flux but to modify the flux path. The magnet flux linked by the armature winding is decreased with this approach while the flux from the magnets is preserved.

Axial flux design and rotor-stator arrangement allow the varying air-gap to optimize the machine performance as shown in Fig. 1.7 (b). This feature affects the machine torque, speed range, and makes this technology promising for many applications requiring flux weakening. The other important advantage of this technique is to be able to change the torque constant of the machine, which results in variable rotor and stator losses. This technique can be applied to double-rotor-single-stator machines too.

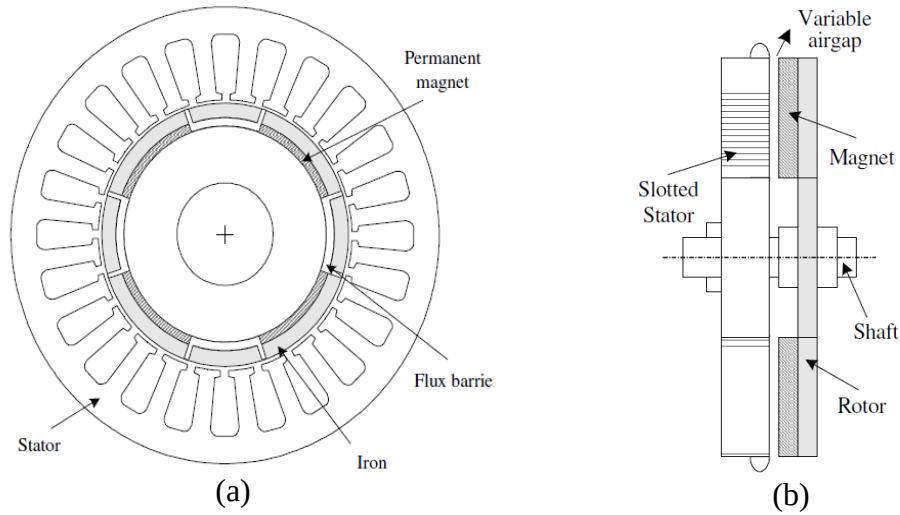


Figure 1.7: Variable speed PM machines; (a) Cross section of the radial flux PM machine for air-gap flux weakening operation, (b) Axial flux PM machine with variable air-gap [57].

A brushless PM machine with a fixed radial air-gap is operated to a higher speed than the normal speed by reducing the magnet strength or average flux per pole. This is achieved by increasing the amount of axial misalignment of the PM rotor resulting in providing axial misalignment between the rotor poles and stator reducing the effective flux over a rotor pole or flux entering the stator as seen in Fig. 1.8 (a) [71].

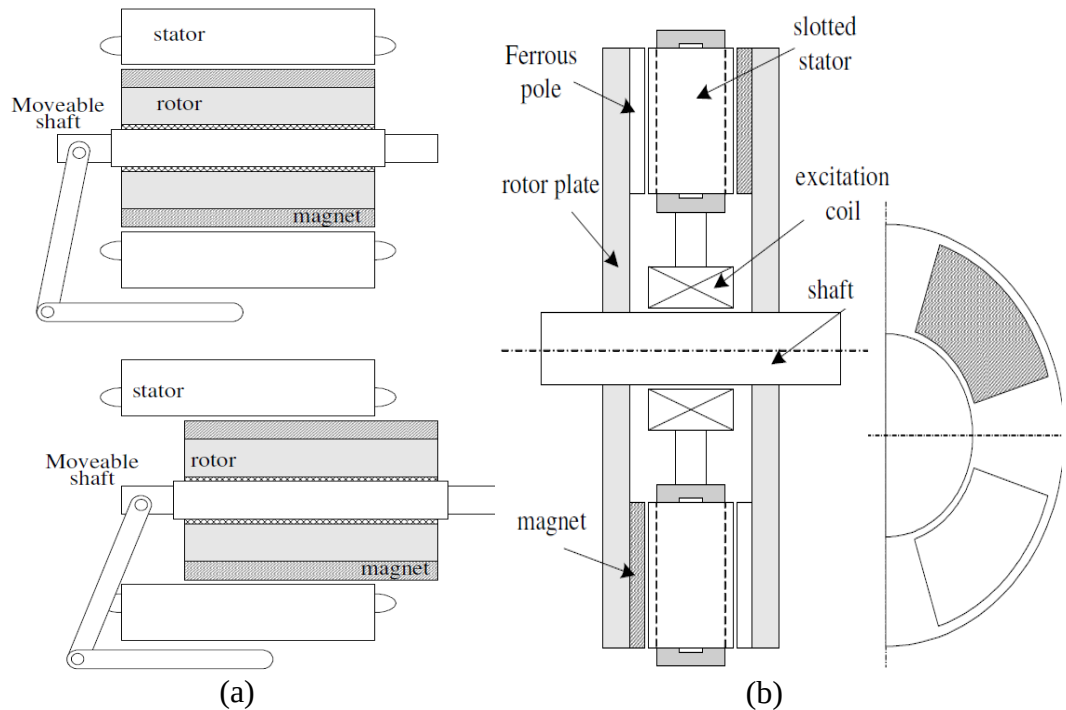


Figure 1.8: Brushless PM machines; (a) variable axial rotor/stator alignment to increase speed capability [18], (b) axial synchronous alternator [72].

An integral constant velocity linear bearing is used to couple the moveable rotor and fixed position machine shaft. An axial flux PM brushless synchronous alternator was designed by Brown et. al. as shown in Fig. 1.8 (b) [72]. This machine combines a variable DC coil excitation in addition to PM excitation. The rotor has two discs mounted on a common shaft. Each disc carries magnets and alternate north and south iron poles which are made of steel.

Axial flux PM machine topology with a DC field winding has been introduced in order to accomplish easy and inexpensive control by Aydin et. al. [73-75]. This new Field Controlled Axial Flux surface mounted PM machine concept has been proposed not only to offer a solution to field weakening operation but also to improve the features of the conventional PM machines by introducing a new axial flux machine concept with flux weakening capability.

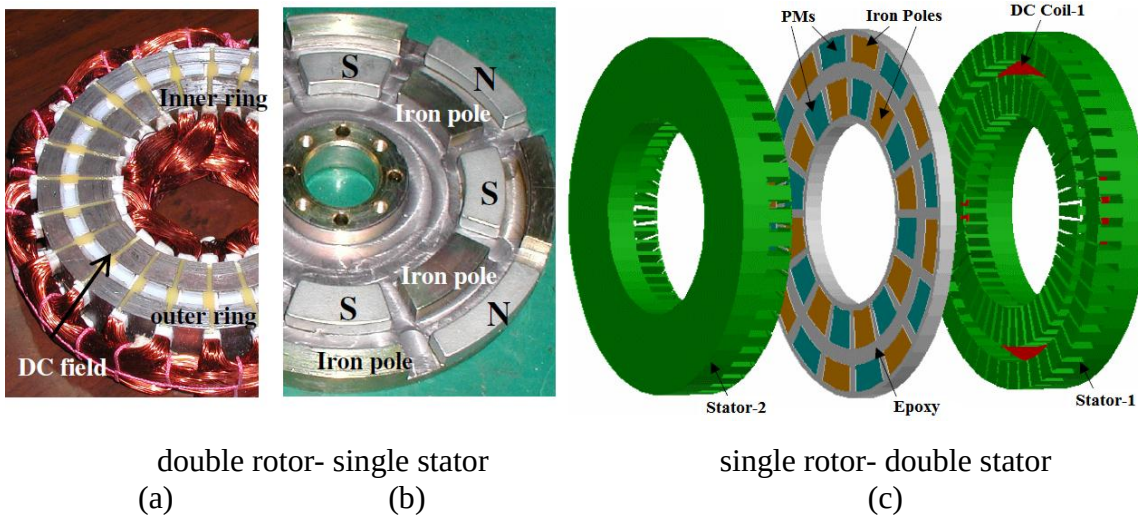


Figure 1.9: Field controlled axial flux PM machines; (a) Disc type stator with both DC field and AC windings, (b) surface mounted PM disc rotor with iron poles, (c) same structure with double stator [75].

Modifying the multiple-rotor-multiple-stator conventional axial flux PM structures by adding one or two DC field windings depending on the machine type to control the air-gap flux and providing a path for the DC flux results in different new axial flux machines with field control capability. Some of these structures are illustrated in Fig. 1.9 and 1.10. Excitation of the DC coil with opposite polarity decreases the field in the consequent poles in both inner and outer portions of the rotor disc thereby weakening the air-gap flux. This topology eliminates the demagnetization risk of the magnets.

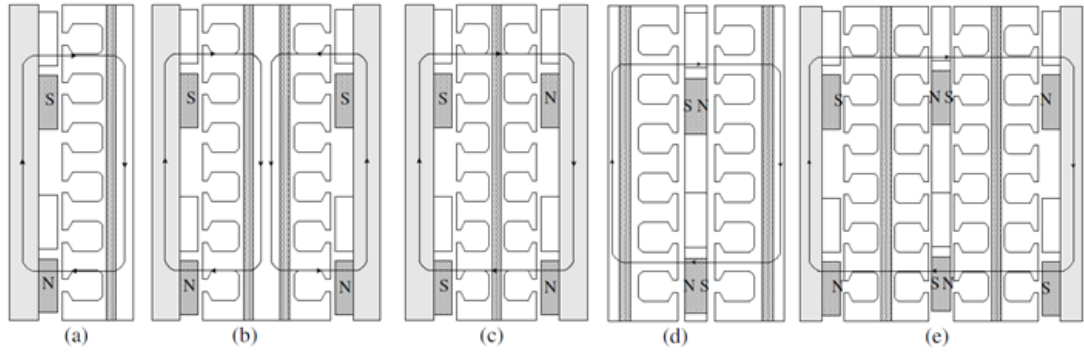


Figure 1.10: Field controlled axial flux PM machines; (a) Disc type stator structure with both DC field and AC windings, (b) surface mounted PM disc rotor with iron poles, (c) same structure with double stator [75].

1.2.3 Flux-weakening and high-speed operating of SPM synchronous machines

Katsuma and Kito [76] presented a brushless surface PM motor with concentrated windings in the stator. They identified criteria for determining the number of rotor poles and the number of stator slots. Konency [77] presented a compact three-phase surface PM machine using concentrated windings around the teeth. The torque ripple and vibrations are minimized while maximizing efficiency and starting torque per unit volume of the winding. Caricchi et. al. [78] presented an innovative inverter topology for supplying an axial flux PM machine using concentrated windings. This new topology permits shaping of the inverter output current waveform to be suitably adjusted with respect to the machine back EMF waveform. Law et al. [79] presented a field-regulated reluctance machine whose stator windings are full pitch concentrated windings. It was shown that this machine is capable of developing 68% greater force density compared to an induction machine hence, this machine generates 34% of the conduction losses of an induction machine. Cros et. al. [80] presented two prototypes of brushless PM motor using a dielectromagnetic material and concentrated windings. Significant gain in the weight of copper (>50%) and in the total cost were achieved. Magnussen and Sadarangani [7] presented a theory for calculating factors for electrical machines equipped with concentrated windings. The effect of the windings factor on the Joule losses has been discussed. Also it was shown that the double-layer concentrated windings has the shortest axial length and hence has the greatest potential to be the most compact unit among the three winding configurations under consideration. Salminen et. al. [81,82] investigated the performance of fractional slot concentrated windings for low speed applications. Cros et. al. [83] presented a comparison of different structures of PM brushless DC

motors with concentrated windings and segmented stator for low power and high efficiency application. EL-Refaie [84] presented a summary of the commercial applications where fractional slot concentrated winding synchronous PM machines are used. In addition, the theory behind FSCW PM machines, design and analysis of FSCW PM machines, achieving high-power density, rotor losses, fault tolerance, parasitic effects, SPM versus IPM, axial-flux, tubular, and flux-switching PM machines and etc. topics are included. G. Dajaku et. al. [85] presented a new method which reduces simultaneously the sub- and the high-harmonics of the winding MMF. The method is based on doubling the number of stator slots, using two identical winding systems connected in series and shifted to each other for a specific angle, using stator core with different tooth width and using different turns per coil for the neighboring phase coils. In addition, the described principles to reduce the MMF harmonics are applicable to any concentrated winding topology.

1.2.4 Synchronous machines having both field windings and PMs in the field poles

Various kinds of synchronous machine structures that have both field windings and PMs have been reported extensively [86–109]. In [86–88], hybrid excitation machines were presented.

In [13–20], automotive generators having PMs between the claw poles were presented. In [95–109], various PM arrangements different from the designed in the thesis are presented.

A new synchronous/permanent magnet hybrid machine has been presented by Luo [86]. The designed hybrid machine has true field regulation capability. The machine can operate at high speed with field weakening capability. It has potentials of achieving high efficiency and high power density due to the use of PM material. The ability to operate as pure PM machine increases its reliability. There is high flux density present in the stator core region between two adjacent PM poles at high speed when weakening the field, which may cause high iron loss in the stator core.

Amara et. al. [87] has presented a study which is examine the principle of hybrid excitation is to combine the advantages of PM excited machines and wound field synchronous machines. Several hybrid excitation synchronous machines divided into

the following two groups as series and parallel hybrid excitation, depending on how excitation flux sources are combined.

1.2.4.1 Series hybrid excitation

For the first group (series hybrid excitation), PMs and excitation coils are in series (see Fig. 11). In these machines, the flux created by excitation coils passes through PMs. Due to the magnetic properties of PMs, some drawbacks can be identified. Since the permeability of PMs is close to that of air, the reluctance of the excitation coil's magnetic circuit is relatively high. Furthermore, the risk of demagnetization should be considered. Fig. 1.11 shows two machines that belong to this first group [88, 95, 96]. Fig. 1.11 (a) shows a structure for which both excitation flux sources are in the rotor, which implies the presence of sliding contacts [87, 95]. Fig. 11(b) shows a structure in which PMs and excitation coils are placed in the stator, avoiding sliding contacts. The rotor of this structure [see Fig. 1.11 (b)] is as simple as that of switched reluctance machines [96].

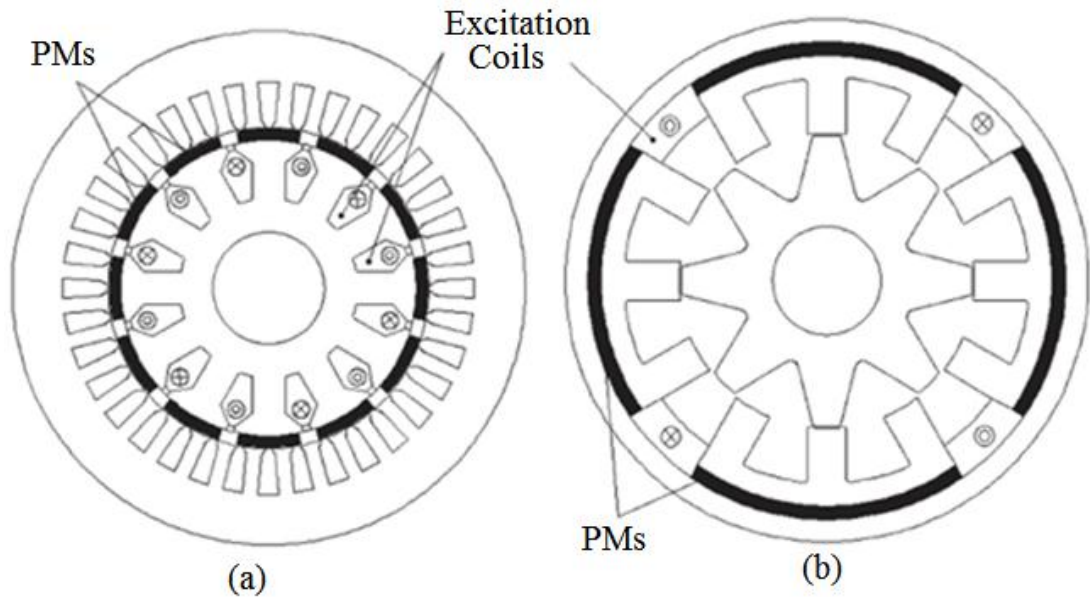


Figure 1.11: Series hybrid excitation synchronous machines; (a) both excitation flux sources, (b) switched reluctance machine [87].

Several researchers have so far developed novel traction devices to respond to the new challenges of the traction and energetic systems applications, proving that machines with two excitation sources are good competitors of the traditional machines. From the excitation circuit point of view, double excited motors can be classified as series or parallel excited machines as investigated in [87].

Fig. 1.12 shows a series double excited synchronous machine (DESM) variant, [88], with its basic principle scheme Fig. 1.12 (a) and cross section Fig. 1.12 (b). The field decrease (and the corresponding speed increase) is achieved by the auxiliary rotor winding supply, which creates a field opposite to the PM flux linkage. The advantage of such a topology consists of its simplicity, while the sliding contact is the major drawback. Radomski [89] suggested the DESM shown in Fig. 1.13 where the PMs are between the adjacent claw poles, and its flux passes toward the stator only due to the rotor field coil, so, this machine is to be considered rather as a wound synchronous motor than as a PM one. For claw-pole alternators used in automobiles, it is known that adding PMs between the adjacent claw poles improves the output power.

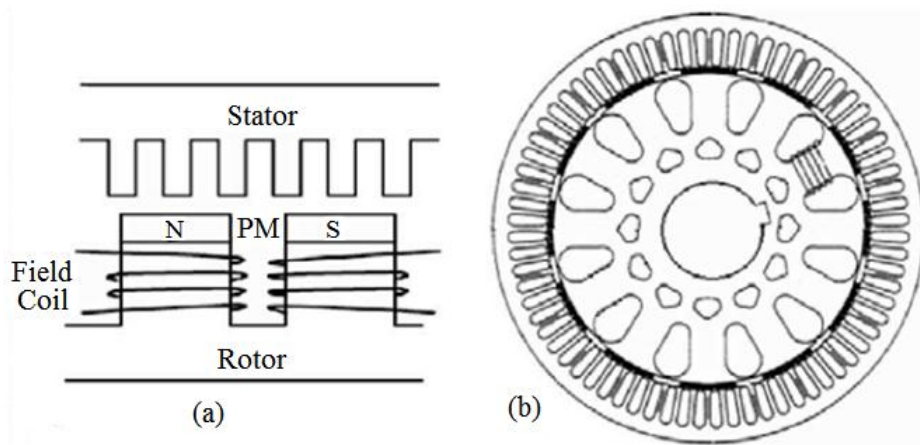


Figure 1.12: A double excited synchronous machine; (a) principle schema, (b) crosssectional view [88].

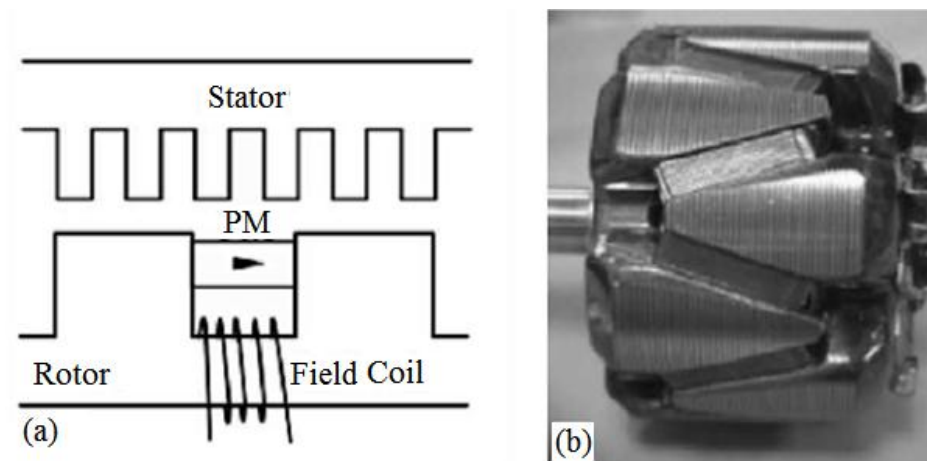


Figure 1.13: A claw pole synchronous machine; (a) principle schema, (b) the rotor structure [89].

Different configurations have been done to improve the output characteristics of the claw pole machines [18,90,91]. Axially magnetized permanent magnets may be added beside the coil (Fig. 1.14 (a)), on the surface of the claws (Fig. 1.14 (b)), and between the claws (Fig.1.14 (c)). In the third case, the permanent magnets act to destroy the inter claw leakage flux of excitation coil. The first two solutions are meant to produce more excitation flux for lower excitation losses. Unfortunately, at low speeds, the influence on the DC output current is small due to magnetic saturation. Different from [18], additional ferrite magnets were installed into the rotor poles in order to increase high torque capability and to reduce low field excitation loss [90, 91].

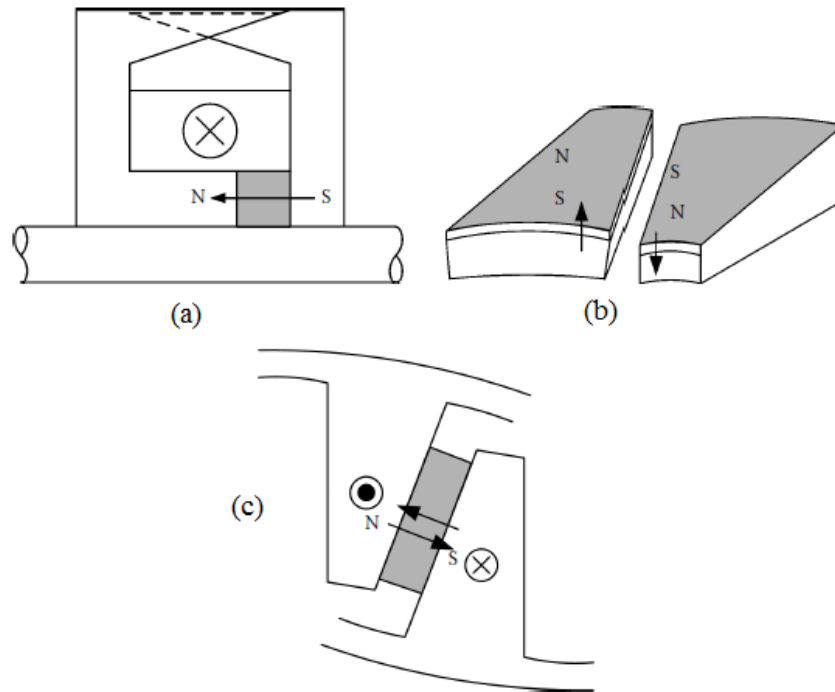


Figure 1.14: Placing additional permanent magnets (PMs) for given stator stack: (a) PMs on the shaft, (b) PMs on the claw surface, and (c) PMs between claws [18].

Wroblewski [92], Amara [93], and Vido [94] proposed a topology of the double excited machine with the auxiliary winding placed on the armature; the principle scheme of their proposals, for one pole pattern, is given in Fig. 1.15 (each author has introduced some specific aspects, but the basic operating principle is the same). With a specific stator winding configuration and a nonmagnetic material that forces a certain flux linkage trajectory, a local air gap flux diminution per one pole can be obtained.

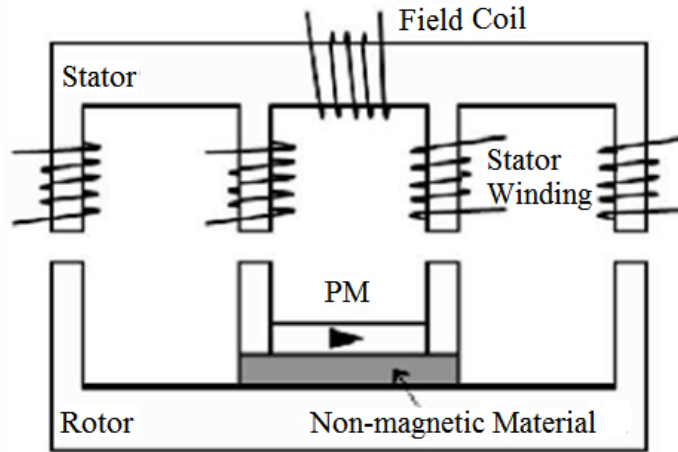


Figure 1.15: Double excited machine with the auxiliary winding placed on the armature [92-94].

Tapia [95] proposes the consecutive poles machine (CPM), where the PM poles alternate with the iron ones, while the auxiliary winding is placed in the stator Fig. 1.16 (a), thus, eliminating the presence of brushes. The field trajectory is 3-D, and a specific material is required for good performances (Soft Magnetic Composites). Rattei [96] offered a mechanical flux-weakening machine solution, with two rotor parts that are fixed or mobile with the shaft and PMs that alternates in polarity (N and S); see Fig. 1.16 (b). The flux weakening consists in rotor parts displacement with α (air-gap angle). The complexity rotor construction and the poor efficiency are the disadvantages of this DESM.

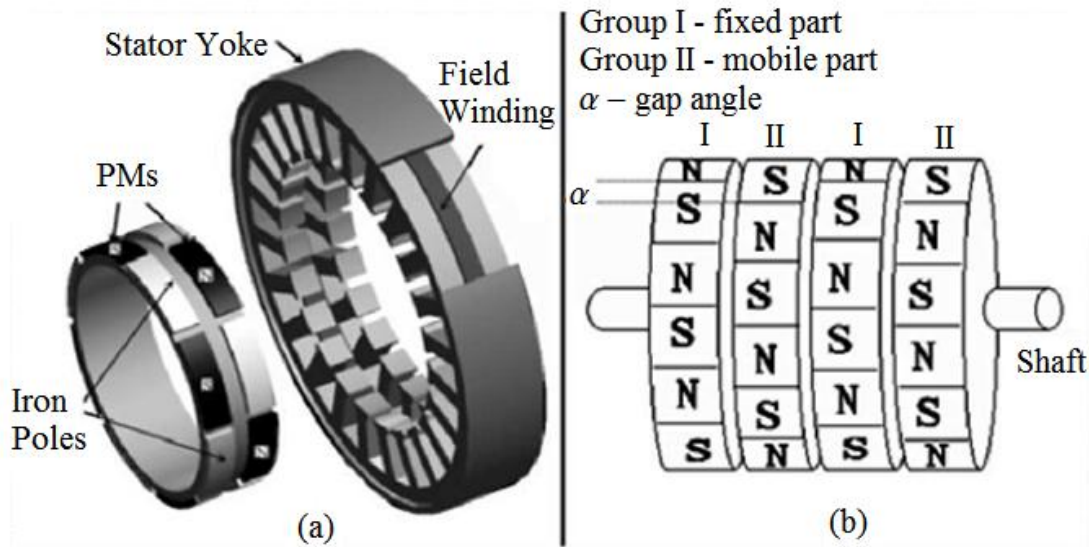


Figure 1.16: Double excited synchronous machines, (a) auxiliary stator windings and rotor with PMs-iron poles [21], (b) the rotor structure (the mobile part is connected to the shaft with a spring) [96].

Details about the operation principles of the previously mentioned machines are also given in [21, 97], where the reasons for using the series DESMs are explained, among which especially the iron losses decrease and efficiency increase in wide speed range operation. The Tapia's machine with CPM topology has been tested and since its speed performances have not shown significant result [97].

To improve output performance of conventional salient-pole synchronous machine given in Fig. 1.17, Hosoi et. al. proposed a new permanent-magnet-assisted conventional salient-pole synchronous machines that have PMs between the field poles [98]. They verified the PM effect of increasing the output power and the terminal voltage by FEM and experiments under sudden short circuits and steady states [98, 99]. Additional to this, it is clarified by Yamazaki et. al. that the additional permanent magnets have the effects of reducing magnetic saturation at the rotor-pole bodies, as well as the effects of increasing the direct flux linkage of armature windings [30,100,101]. In this thesis, same technique is used for development of large FSCW SPSG.

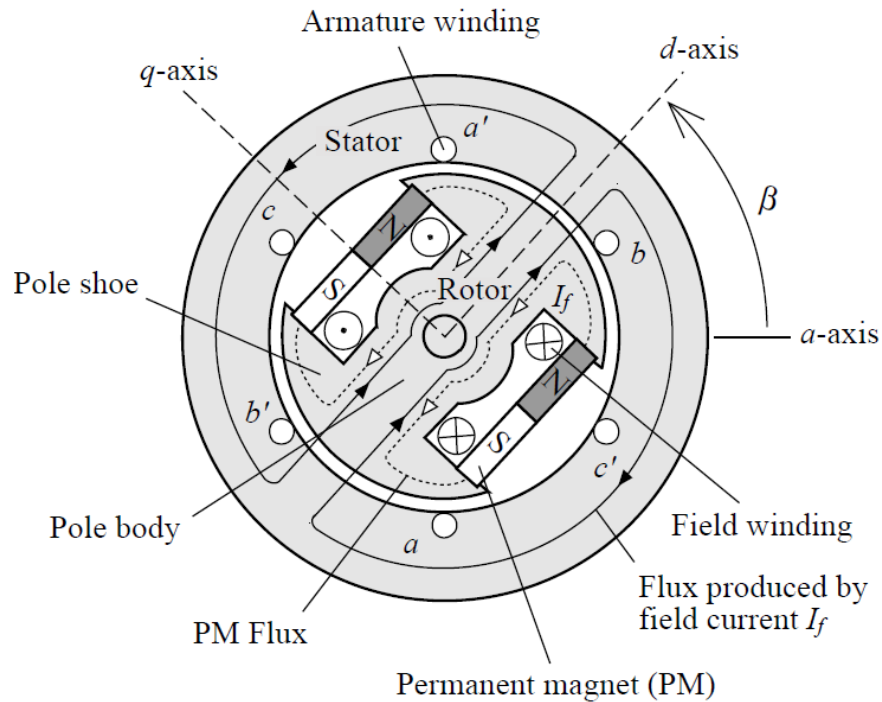


Figure 1.17: Cross section of an elementary PM-assisted conventional SPSM.

1.2.4.2 Parallel hybrid excitation

For parallel hybrid excitation synchronous machines, the excitation flux created by PMs and excitation coils have different trajectories. The flux created by excitation

coils does not pass through PMs. Compared to the first group; parallel hybrid excitation allows a wide variety of structures to be realized. They illustrate the diversity of structures based on this principle. Fig. 1.18 (a) and 1.18 (b) presents structures for which both sources are placed in the rotor [86,102]. Fig. 1.18 (c) presents a structure where PMs and excitation coils are located in the stator [103].

Several other authors presented various synchronous machines having both windings and PMs in the field poles; for example, see [21], [104-109]. These references are only going to be included for benefit of readers but are not discussed in detail in this section.

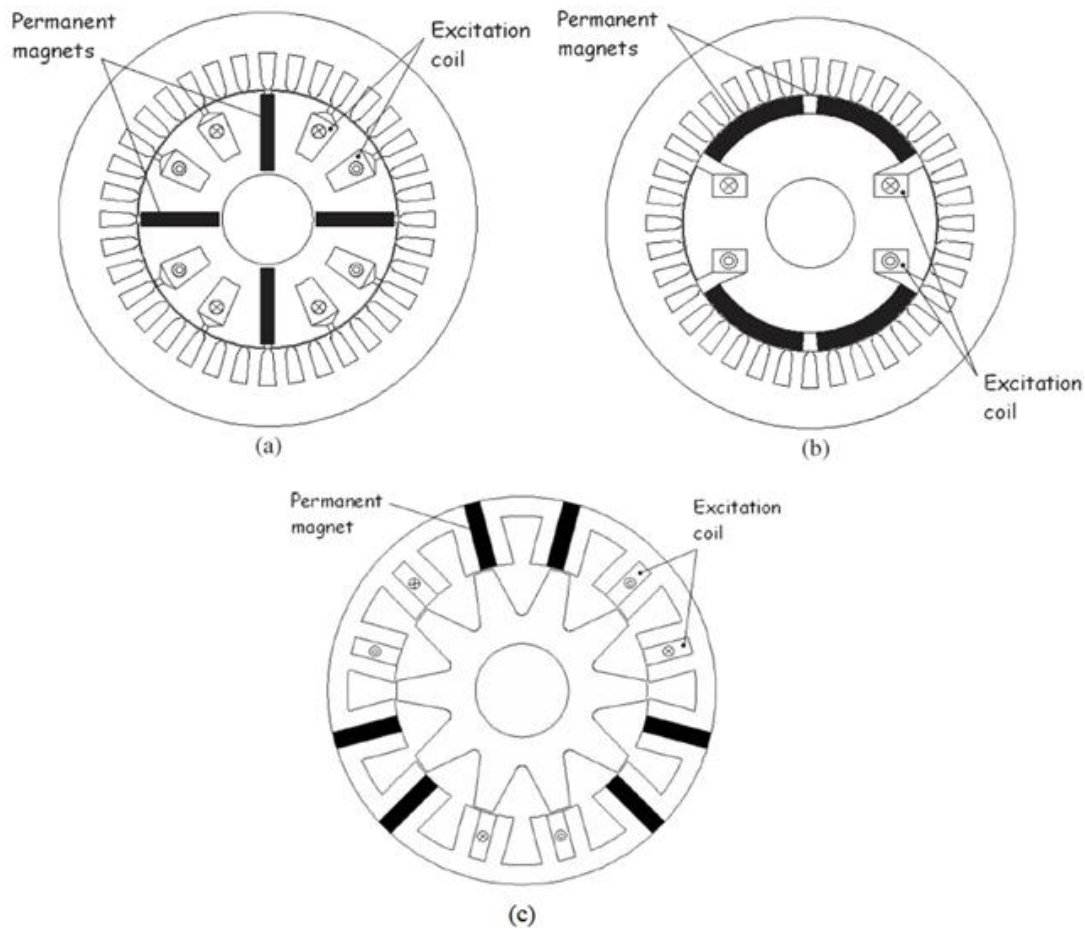


Figure 1.18: Parallel hybrid synchronous machines with both excitation flux sources are placed in the rotor [87].

1.3 Hypothesis

SPSGs are used in the majority of hydroelectric, thermoelectric and wind power plants. In these machines, the output power is determined by the MMF of the field windings on the rotor and it is proportional to the cross sectional area of the field

windings. However, to be able to maintain the total machine size, the rotor pole-bodies should be reduced for maximum MMF. As a result of decrease in the permeability of the rotor-pole body because of the reduction in rotor pole-bodies, saturation will occur in the pole-bodies. The magnetic saturation limits the armature terminal voltage and requires more excitation power and the additional losses in the damper windings are reduced the efficiency and increased the total machine weight. Eventually, the output power of the machine does not increase despite the increase in the MMF. To overcome this design limit, FSCW SPSG is proposed and is developed by inserting additional PMs between the adjacent rotor-pole shoes.

By implementing the Fractional Slot Concentrated Winding (FSCW) technique to a PM machine, high slot fill factor and short end turns when coupled with segmented stator structures, low cogging torque, good flux-weakening capability, decreasing in the weight, simple structure, higher efficiency, and higher permeability of the iron cores may be obtained. Same method can be implemented the SPSG to be able to achieve the same developments. In the process of implementation of FSCW technique, some significant advantages of FSCW technique over distributed windings including; low copper usage and low copper losses, significantly higher slot fill factor, reduction in the machine total length and simpler construction are utilized. The basic reason underlying these are that fractional slots concentrated windings refer to windings that encircle a single stator tooth; eliminating any end-winding overlap with other phase windings thus prevents saturation of the poles.

For development of the FSCW generator placed PMs between the adjacent pole shoes are used. The main porpoise of the PMs are not to help to increase the excitation; they mainly used for produce fluxes reversed to main fluxes flowing on each pole body which enables to prevent the saturation of the pole body. Nevertheless, the terminal voltage of the generator will increase because of the position (polarization direction) of PMs. Using this saturation reduction method, output parameters of the generators such as terminal voltage, output power and loading capacity may be increased or the dimensions of the generator may be decreased without changing the output voltage and power. In this study, the dimensions of the FSCW generator are decreased instead of increasing the output variables to be able to achieve the highest efficiency.

2. FIELD (FLUX) WEAKENING

In this section, general knowledge about field in other name flux weakening operation is explained to be able to enlighten the FSCW technique. Actually, the main purpose of this study is not to use the field weakening, as a natural result of FSCW technique (one coil per one stator tooth) field weakening has been occurred because of the very large stator slots. In addition to this, FSCW topology has been used for flux weakening operations for achieving constant-power speed range in the small PM synchronous machines and this topology is not used in larger electrical machines because of the some important factors like efficiency and smooth torque production as it mentioned in the introduction. In this thesis, FSCW topology is implemented to a large SPSG to be able to achieve developed lighter and also cheaper SPSGs having pole body cores with a higher saturation level without decreasing the efficiency, and also output power and SPSGs having lower cogging torque. Ideal field weakening operation and parameters are discussed. Conditions for maximum and optimal field weakening operation are given.

2.1 Field Weakening Operation

Significant increase in the machine inductance in order to achieve the critical condition for providing wide speed ranges of constant-power operation may be achieved by properly designing the machine's stator windings using concentrated, fractional-slot stator windings. Concentrated windings refer to windings that encircle a single stator tooth, eliminating any end-winding overlap with other phase windings. The conditions for optimal flux weakening can be achieved while simultaneously delivering sinusoidal back-EMF waveforms and low cogging torque.

The phasor diagram of a typical PM machine drive is shown in Fig. 2.1 at base and high speeds. Maximizing the machine torque without exceeding either the current or voltage limit requires proper adjustment of the excitation phase angle with respect to the rotor position. Since torque production is dominated by the fundamental component, maximum torque can be achieved if the torque angle associated with the

fundamental voltage component is adjusted to 90° electrical. However, this condition is subject to the constraint that the phase current must not exceed the rated current. If it does, the torque angle must be reduced until the rms current falls within the rated current limit. The fundamental component vector diagram in Fig. 2.1 shows this operating condition with 90° for two different operating speeds above the corner speed. The current angle is defined as the angle between the q -axis (back-emf axis) and the current vector.

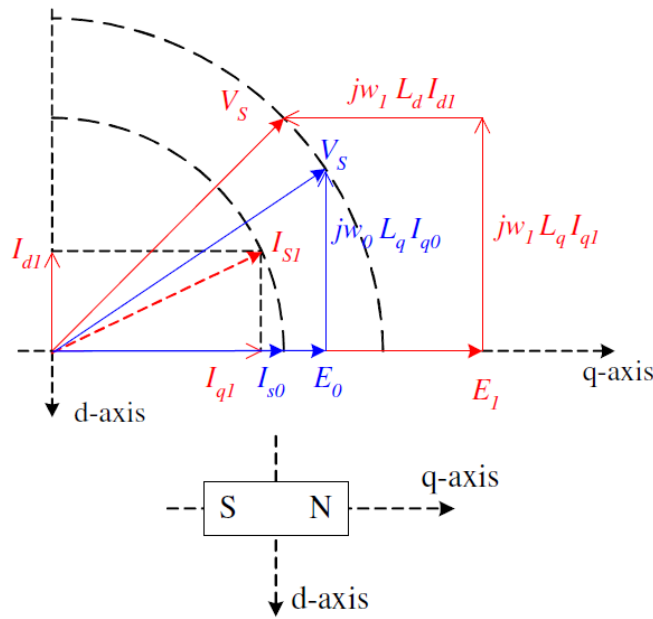


Figure 2.1 : Phasor diagram of a PM machine [110].

It can be observed that the current vector gradually shifts towards the negative d -axis (magnet flux axis) as the rotor speed increases in order to counteract the magnet flux (i.e., flux weakening). The equivalent circuit of this kind of machine comprises the inductance and the back-EMF voltage which is the product of magnet flux linkage (Ψ) and the machine electrical speed (ω). The magnet flux lies along the d -axis and the back-EMF phasor which is 90° phase advanced lies along the positive q -axis. The machine torque is generated both by the magnets and by the saliency and depends on the angle between the current phasor and the q -axis. The current phasor must be aligned with the q -axis in order to obtain maximum output torque for non-salient machines. As for the salient pole machines, the current phasor is slightly shifted towards the d -axis to achieve maximum torque for a given value of current. At high speeds, flux weakening becomes necessary since the machine back EMF can cause the stator voltage to exceed the maximum inverter output voltage. Therefore, the

voltage drop $j\omega L_a I_a$ becomes negative by adding a negative d -axis current, which results in reduced total air-gap flux and the excess back-EMF compensation reducing the machine terminal voltage. Some electrical machines as separately excited DC commutator motor drive show an ideal field-weakening characteristic. In this drive the flux is controlled by the field current; the torque is the product of the armature current and the flux, and the voltage is the product of the speed and the flux. Fig. 2.2 shows the ideal field-weakening characteristics for a drive with a limited inverter kVA capability. At low speed, rated current I_C , and rated flux are used to give rated torque T_K . The voltage and output power both rise linearly with speed. At rated speed, voltage equals the rated voltage V_C . Above rated speed, the voltage is kept constant by decreasing the flux, and hence the torque, in inverse proportion to speed. As the output power is constant this is called the constant-power, field weakening or flux-weakening region [35].

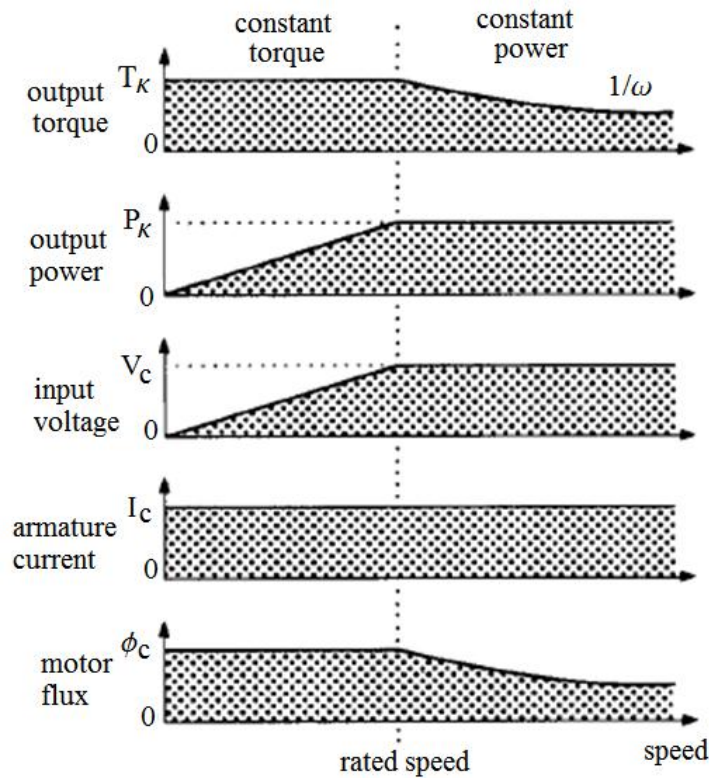


Figure 2.2 : Ideal field-weakening drive characteristics [111].

Real electrical machines do not have flat output power against speed characteristics above rated speed. In Fig. 2.3 the dashed line is the ideal field-weakening characteristic and the solid line is the actual characteristic. Rated power P_K , is the output power at rated speed with rated torque. The inverter utilization is the ratio of

rated power to the ideal output power. This is less than unity as the motor does not have unity power factor and 100% efficiency under rated operating conditions. The constant-power speed range (CPSR) is the speed range over which rated power can be maintained. The widely used vector-controlled induction motor drive offers constant-power speed ranges of up to 4:1 [112,113].

The separately excited DC machine has separate windings for the flux-producing and torque-producing currents. Brushless synchronous AC machines have a single stator winding which generates a rotating current phasor. Flux-weakening is achieved by rotating the current phasor towards the least inductive axis and hence reducing field current. In PM machines the flux is mainly produced by magnets and flux-weakening is achieved by using a different PM whose polarizations of the poles are reverse according to other PM.

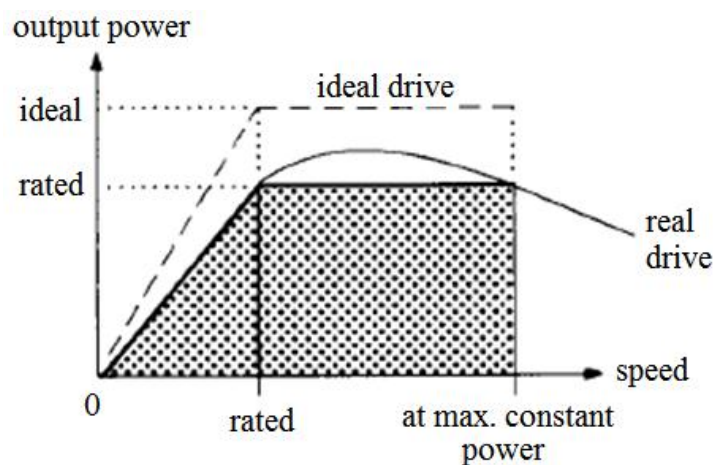


Figure 2.3 : Definition of field-weakening parameters [111].

Five main classes of brushless synchronous AC motor drive can be defined, based on whether there is a theoretical finite maximum speed limit owing to voltage-limit constraints. These are:

- a) finite maximum speed SPM drive
- b) infinite maximum speed SPM drive
- c) infinite maximum speed synchronous reluctance
- d) finite maximum speed IPM drive
- e) infinite maximum speed IPM drive.

Note that all synchronous reluctance drives have no theoretical maximum speed and that this does not necessarily imply good field-weakening performance as the output power may be very low at high speeds.

2.2 Maximum Torque Field Weakening Control

Each of the five drive classes has a particular field weakening control strategy to obtain maximum torque (and hence power) at any speed within the inverter volt-ampere rating. It is based on the work by Morimoto et al. [42]. A normalized dq model with the magnet flux in the d -axis and the q -axis being the most inductive axis is used [40]. This is the opposite of the usual convention for synchronous reluctance motors [114] but is consistent with that used in interior PM drives [35]. With the saliency ratio $\xi = L_q/L_d$ may be given in (2.1).

$$\begin{aligned} V_{dn} &= -\omega_n \xi L_{dn} I_{qn} \\ V_{qn} &= \omega_n L_{dn} I_{dn} + \omega_n \Psi_n \\ T_n &= I_{qn} [\Psi_n - (\xi - 1) L_{dn} I_{dn}] \end{aligned} \quad (2.1)$$

Note the use of the subscript n indicate normalized parameters. The current angle θ is defined as the angle by which the stator current (or MMF) leads the q -axis. Thus; $I_{qn} = I_n \cos \theta$ and $I_{dn} = -I_n \sin \theta$. So, reorganizing the equations according to new currents, maximum torque may be achieved as (2.2).

$$\begin{aligned} V_{dn} &= -\omega_n \xi L_{dn} I_n \cos \theta \\ V_{qn} &= -\omega_n L_{dn} I_n \sin \theta + \omega_n \Psi_n \\ T_n &= I_n \left[\Psi_n \cos \theta + \frac{1}{2} (\xi - 1) L_{dn} I_n \sin 2\theta \right] \end{aligned} \quad (2.2)$$

2.3 Optimal Field Weakening Designs

It is well known that the condition for optimal flux weakening in an SPM machine occurs when the machine characteristic current equals the rated current (i.e. $I_x = I_R$, where I_R is the rated current of the machine) [8,37] as it given in (2.3).

$$I_x = I_R = \frac{\Psi_m}{L_d} \quad (2.3)$$

Unfortunately, the inductance values of SPM machines are typically low with conventional stator winding designs because the permanent magnets mounted on the rotor surface behave as large air gaps in the machine's magnetic circuit. Furthermore, there is limited opportunity to lower the magnet flux linkage Ψ_m in SPM machines without degrading the machine's torque production capability. As a result, the characteristic current values for SPM machines tend to be significantly higher than the rated current, causing severe limits on the machines' constant-power speed range during flux weakening operation.

The optimal field-weakening performance can be obtained from any drive design lying on the optimal IPM design line. These designs fall into three categories:

- a) synchronous reluctance motor drives with infinite saliency,
- b) interior permanent magnet motor drives where $\Psi_m = L_d I_0$,
- c) surface permanent magnet motor drives where $\Psi_m = (\sqrt{2})^{-1}$.

Note that all these designs share a common characteristic: the flux in the motor is zero when rated current is applied to the d-axis of the motor. With an infinite saliency synchronous reluctance motor drive, $L_d = 0$, whereas with the PM machines the stator flux linkage due to the stator current is precisely cancelled by the magnet flux. Clearly, infinite saliency ratio synchronous reluctance motor drives are impossible. However, practical high saliency designs may offer sufficiently good field weakening performance. The synchronous reluctance motor is attractive because it does not require magnets. This reduces the cost and eliminates problems of magnetization and demagnetization. The ideal constant-power speed range of a synchronous reluctance motor drive is approximately half the saliency ratio.

3. FRACTIONAL SLOT & CONCENTRATED WINDING CONFIGURATIONS

In this section, a technique to increase the phase inductance and hence to give rise to the leakage flux is explained. The winding inductance plays a key role in determining various aspects of the performance of the electrical machines. These include the flux-weakening capability, the reluctance torque, and the current ripple. Advantages and disadvantages of using concentrated windings in the stator of the electrical machines are discussed comparing with conventional winding configurations. Manufacture of concentrated windings with powdered iron cores is explained. In addition, comparison of double and single layer windings are made to be able to emphasize the importance of the double layer windings in the following sections.

3. 1 Winding Configurations

The winding configurations which are most commonly employed for three-phase radial-field PM brushless machines can be classified as [115]:

- a) overlapping, either distributed or two slot/pole/ phase ($q=2$) [Fig. 3.1 (a)] or concentrated [Fig. 3.1 (b)] ($q=1$);
- b) non-overlapping, i.e., concentrated, with either all teeth wound [Fig. 3.1 (c)] or alternate teeth wound ($q=0.5$) [Fig. 3.1 (d)].

Non-overlapping windings will be referred to as FSCW for the rest of this thesis. All teeth wound winding will be referred to as double-layer (DL), while alternate teeth wound will be referred to as single-layer (SL).

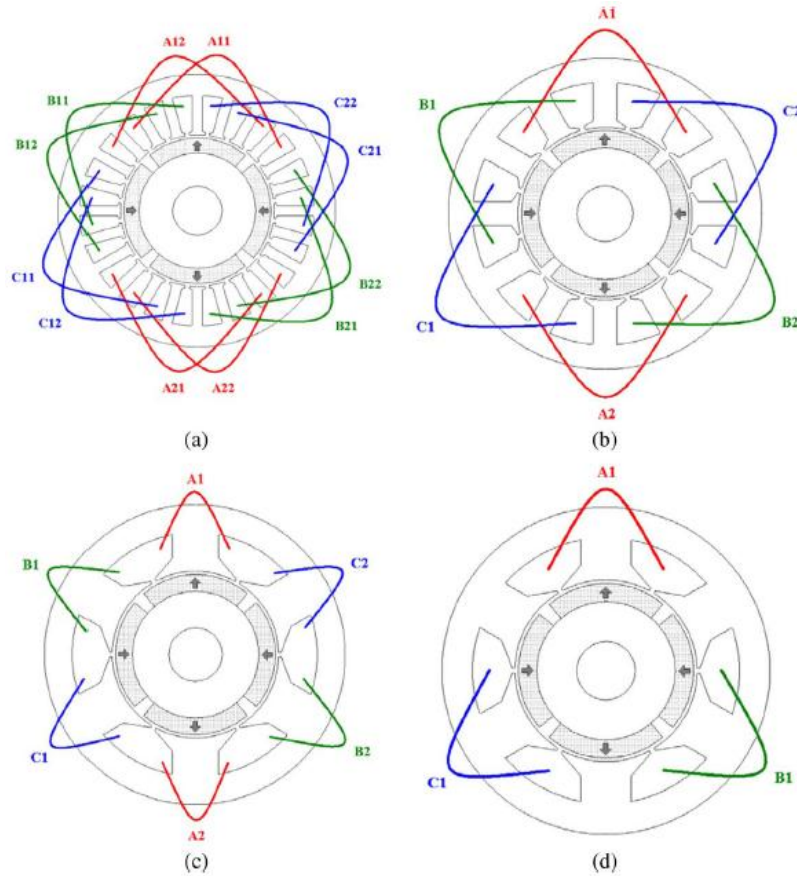


Figure 3.1 : Typical stator winding configurations (four pole); (a) Twenty-four slot, overlapping (distributed). (b) Twelve slot, overlapping (concentrated). (c) Six slot, non-overlapping, all teeth wound. (d) Six slot, non-overlapping, alternate teeth wound [115].

3. 2 Comparison of Distributed and Concentrated Windings

Concentrated windings are those windings with all coil sides of a certain phase concentrated in a single slot under one pole, thus requiring deep slots. Distributed windings result in a more efficient utilization of the armature periphery. In general, distributed windings can make better use of the stator and rotor structure and also decrease harmonics comparing to concentrated windings [116]. On the other hand, concentrated windings offer some significant advantages over distributed windings. These include:

- a) simpler construction,
- b) significant reduction in the copper volume and copper losses in the end region
- c) no large end connections because of concentrated coil winding,

- d) low copper usage and low copper losses,
- e) significantly higher slot fill factor,
- f) reduction in the machine total length [7,10,117],
- g) reduction in machine manufacturing weight and also cost,
- h) no mutual inductance between phases causing a higher fault tolerance [118],
- i) compatibility with segmented stator structures that makes it possible to achieve higher slot fill factor values [119,120],
- j) provide higher inductance compared to distributed windings for the same magnet flux linkage.

However, there are a number of well-known disadvantages associated with concentrated windings such as [121,122]:

- a) higher cogging torque,
- b) potential for higher acoustic noise and vibration,
- c) low winding factor,
- d) lower output torque due to a low winding factor,
- e) decrease in saliency ratio,
- f) higher eddy-current losses in high-speed PM machine applications.

Since a distributed overlapping winding generally results in a more sinusoidal MMF distribution and EMF waveform, it is used extensively in PM brushless ac machines. On the other hand, FSCW synchronous PM machines have been gaining interest over the last few years. This is mainly due to the several advantages that this type of windings provides. These include high-power density, high efficiency, short end turns [7,117], high slot fill factor particularly when coupled with segmented stator structures, low cogging torque, flux weakening capability, and fault tolerance. Table 3.1 summarizes the key differences between distributed windings and concentrated windings. Another major advantage is that concentrated windings provide higher inductance compared to distributed windings for the same magnet flux linkage. This is the fundamental reason why concentrated windings have the potential to significantly improve the flux-weakening capabilities of SPM machines.

Table 3.1 : Comparison of distributed and concentrated windings [84].

	Distributed Windings	Concentrated Windings
Typical copper slot fill factor	35%-45%	50%-65% (if coupled with segmented stator structures)
Stator structure	Continuous laminations	Continuous laminations or segmented structures
End turns	Long overlapping	Short non-overlapping
Torque producing stator space harmonic component	Fundamental	In most cases (except for 0.5 slot/pole/phase) a higher order harmonics

3. 3 Powdered Iron Cores & Pre-Pressed Windings

Powder Metallurgy has been used for many years as a cost effective method of producing high volumes of consistent magnetic components for DC and hard magnetic applications. The method allows high material utilization, precise material control and the ability to produce relatively complex shapes. Recent advances in materials research have produced a soft magnetic composite material which offers AC performance approaching that of steel laminations for a similar material cost [123,124]. Therefore the manufacturing advantages of powdered metallurgy may be exploited in the manufacture of electrical machines [125-128]. There have been a number of occasions where powdered iron has been considered as a direct replacement for lamination steels. In virtually every case, the machine has been shown to give poorer performance because the powdered iron has a lower unsaturated permeability, lower saturation flux density, and increased iron loss. Due to the segmentation of the stator core, it is possible to use pre-made coils in the stator. The coils are made up of rectangular copper conductors manufactured under tension. The result is a high slot fill factor of 0.78.

Due to the relatively large cross-section area of the conductors, the eddy-currents induced at increasing or fixed frequency are not negligible. So, one of the key advantages of FSCW is the ability to achieve significantly higher copper slot fill factor (compared to conventional laminated stator structures) if coupled with segmented stator structures particularly if the windings are prepressed.

This can have a significant impact on the machine power density. The copper slot fill factor is defined as (3.1).

$$K_{cu-fill} = \frac{A_{cu}}{A_{slot}} \quad (3.1)$$

where A_{cu} is the total copper area and A_{slot} is the total slot area. Several methods have been proposed to achieve this goal. This section will cover the key papers addressing various concepts of segmenting the stator structure to significantly increase the slot fill factor and reduce manufacturing cost.

The windings were made with the aim of maximizing the copper cross-sectional area within a slot, in order to minimize the per-unit resistance of the machine. The turns were machine wound onto a former coated with epoxy in a wet layup process. They were then pressed in a die and cured under load. The finished coils were then tape wrapped to form a layer of ground wall insulation. Polymeric wire insulation was found to survive compaction under high pressure up to 800 MPa. To optimize the performance of the powdered iron machine the design may be radically altered as follows [129].

1. The number of teeth was reduced to three teeth per pole pair. This improved the tooth aspect ratio for pressing and aided the winding process.
2. Instead of a fully pitched winding, the windings enclosed a single tooth (120° electrical). Thus, they formed a bobbin shape which was simple to wind and easy to assemble into the stator.
3. The powdered iron stator core was split to form tooth and core back sections, each of which could easily be pressed. The two sections allowed a preformed coil to be placed over the tooth, before the tooth was slotted into its core back section, as shown in Fig. 3.2. The teeth segments were then bonded together and shrunk into a standard aluminum frame as shown in Fig 3.3 (a).
4. The axial ends of the stator teeth were rounded to maintain close thermal contact with the winding, while also maximizing the stator tooth area. The smooth tooth profile removed the need for a thick slot liner.
5. The core back was axially extended over the end winding, thereby allowing a shallower core back and larger slot area.

6. The coil was performed and then pressed to 450 MPa to give a copper fill factor (ratio of copper area to total slot area) of 78% as shown in Fig. 3.3 (b) and Fig. 3.4.
7. The rotor or stator should be skewed by one half slot pitch to reduce cogging torque.

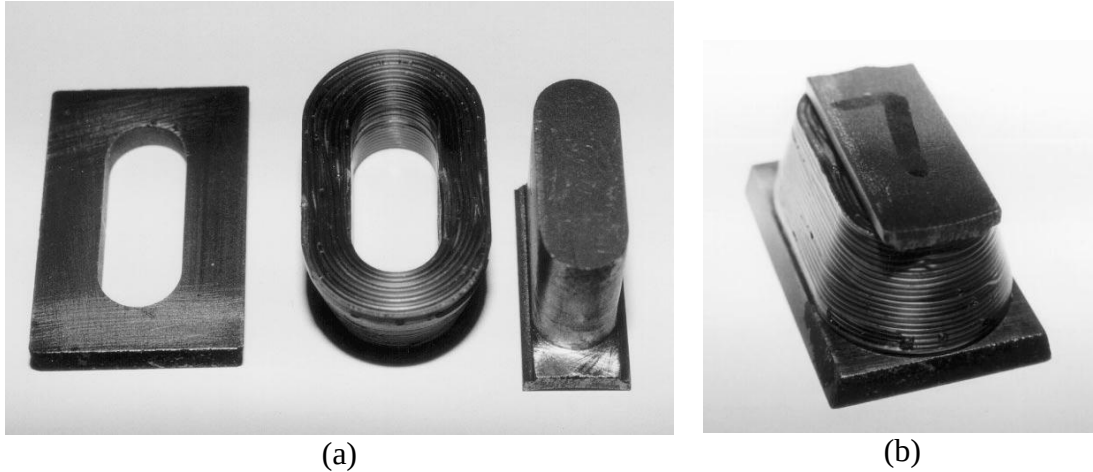


Figure 3.2 : Stator components; (a) Manufactured core components and coil, (b) Tooth assembly [129].

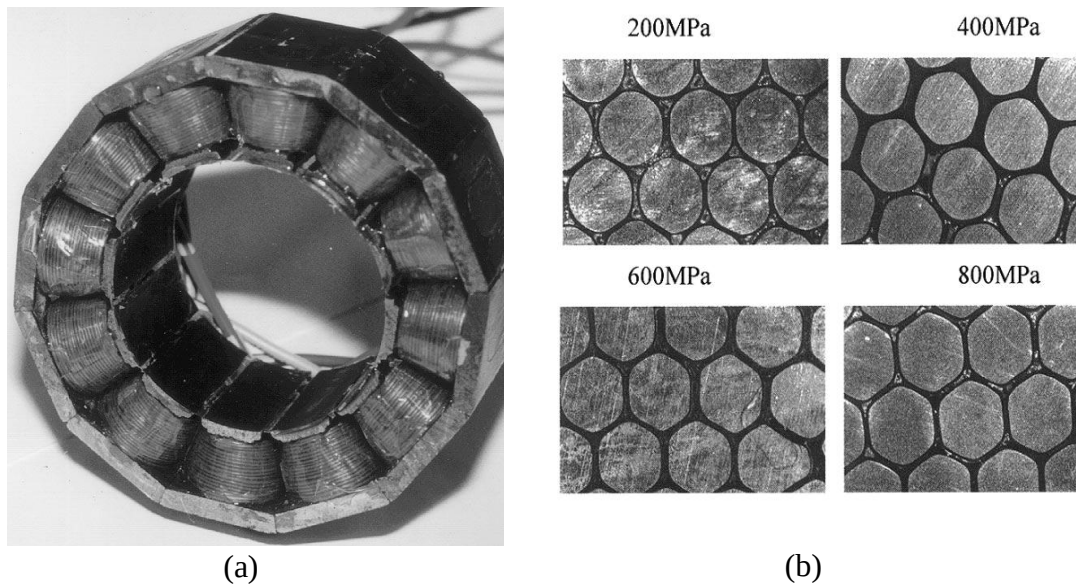


Figure 3.3 : Complete stator and coil sections; (a) Assembled stator before insertion into core, (b) pressing trial results-coil sections [129].

A copper fill factor of around 64% was achieved by machine winding alone. The copper fill factor increases with applied pressure, reaching a practical maximum value of approximately 81% at around 400 MPa in practice, above which point there is little to be gained by further increasing pressure. Fig. 3.3 (b) shows sections

through coils pressed to 200, 400, 600, and 800 MPa. Clearly, the turns are deformed from circular toward hexagonal cross section at around 400 MPa. Above this pressure (600, 800 MPa), the sections appear almost fully dense, supporting the graphical results of Fig. 3.4.

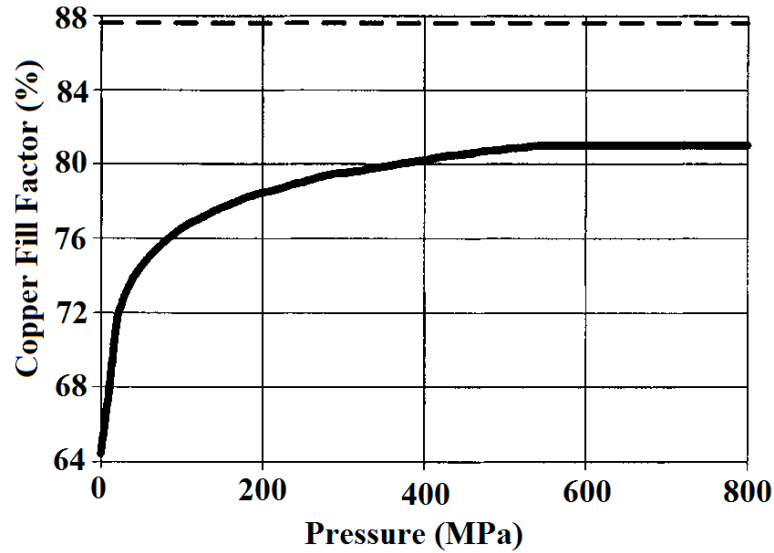


Figure 3.4 : Pressing trial results-copper fill factor variation with pressing pressure (dotted line is theoretical maximum) [129].

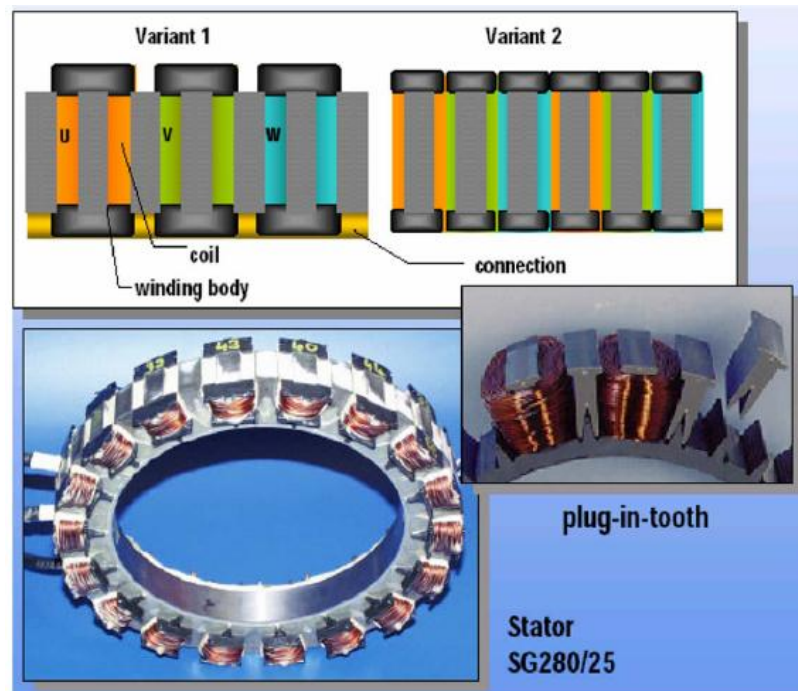


Figure 3.5 : Joint-lapped core machine; (a) Cross section of a joint-lapped core machine (75% fill factor reported). (b) Joint-lapped core after winding.

Similar values of slot fill factor values have been reported in case of segmented laminated stator structures using plug-intooth technique [84]. Such configuration is

shown in Fig. 3.5 [84]. In [120], more recently, Akita et. al. reported a 75% slot fill factor using a “joint-lapped core”. There have been several publications addressing the use of FSCW in conjunction with segmented stator structures for various types of PM machines. It was shown that using rectangular wires instead of conventional round wires reduces the end coil region by 15% and a higher slot fill factor can be achieved. It was shown that using an improved stator tooth configuration where the air gap is larger at the high stress points helps reducing the vibrations and noise in the machine [130]. It was shown that by appropriately adjusting the pole-arc to pole-pitch ratio, the optimum ratio for cogging torque minimization that was derived for SPM machines is equally applicable in the case of IPM machines. It was also shown that the cogging torque in case of the non-overlapping concentrated windings is almost half that in the case of full-pitch overlapping windings [131].

3. 4 Comparison of the Winding Layers

However, single-layer windings which have coils wound only on alternate teeth are only feasible when the number of slots is a multiple of 6. For double-layer windings, each tooth carries one coil and the slot is usually divided vertically. If the number of slots is not odd, single-layer windings are also possible. In addition, the number of the winding layers influences the winding factor. Some properties of single and double-layer concentrated windings are compared as Table 3.2.

Table 3.2 : Comparison of the winding layers.

Winding Layers	SL	DL
Winding Factor	higher	lower
Slot/pole Combinations	few	many
End-windings	longer	shorter
Phase inductance	higher	lower
Slot fill factor	higher	lower
Tolerance to faults	better	worse
Rotor Loss	higher	lower
EMF	more trapezoidal	more sinusoidal
Harmonic content of MMF	more harmonics	fewer harmonics
Manufacturing	easier	more difficult for conventional

3. 5 Choice of q Value

It has been shown that there are several q values in the fractional-slot category that can support concentrated windings [7,9]. However, different q values can result in

very different machine characteristics. It is very important to select the q values that can achieve the highest machine performance. The criteria for choosing the preferred q values have been identified by various authors [7,9,132] and are summarized here:

- The winding factor for the spatial frequency that matches the rotor magnet fundamental spatial frequency (henceforth referred to as simply the synchronous frequency) should be as high as possible. These lead to high effective numbers of turns and, hence, lower current for the same torque.
- The lowest-common-multiple (LCM) of the number of stator slots and the number of rotor poles should also be as high as possible. The harmonic frequency that corresponds to this LCM order value represents the cogging torque frequency. As a result, choosing q values to increase this LCM value raises the cogging torque frequency and lowers its magnitude.
- The greatest-common-divisor (GCD) of the product of the number of stator slots and the number of rotor poles must be an even number. This GCD value is an indication of the machine's symmetry. If it is an even number, the net radial force on the machine will be very low.

In addition to these established criteria, it is also desirable to choose a q value that can support single-layer concentrated windings (i.e., one stator phase coil occupying each slot). Only certain q values are compatible with single-layer windings [7, 9]. One advantage of single-layer stator windings is that they are easier to fabricate than double-layer windings that have two phase coils sharing each slot. More relevant to the topic of this study, single-layer stator windings create sub-harmonic spatial flux components (i.e., sub-harmonics of the synchronous frequency) that are larger than those for double-layer windings. These sub-harmonic flux components are valuable because they contribute leakage inductance terms that increase the total phase inductance, helping to decrease the value of the characteristic current **(2.3)** in order to achieve wide speed ranges of constant-power operation.

4. PERMANENT MAGNETS

PMs are necessary components in many fields of technology because of their ability to provide a magnetic flux without windings, and have applications in a wide range of devices [133] such as Electro-Mechanical Machines and Devices, Automation Applications, Mechanical Force and Torque Applications, Office equipment, Computer Peripherals, Microwave/MM-Wave Devices, Electron Ion Beam Control Sensors, Acoustic and Electric Signal Transducers, Medical Electronics and Bioengineering, Transportation and Advertising.

Developments, physical and chemical characteristics, manufacture, application areas, price guides and detailed comparison of the PMs are explained in the following sections.

4.1 Developments of PM Materials

The development of hard magnetic materials has been very rapid, with the advent of rare-earth PMs in the last few decades. Fig. 4.1 shows the important changes in PMs in the last century. The improvement in PM materials over the past 90 years can be tracked by the $BH_{\max}$ value in the graph.

In 1931, the first hard magnet alloy based on Fe, Ni and Al (Alni) was developed in Japan, followed by improvements from many researchers in different countries. Because of their higher coercive forces and much lower cost, hard magnetic ferrites became suitable for the electrical machines for the first time in the 1950s.

In early 1960s, the first of newly developed rare-earth magnets was a hexagonal SmCo compound with the CaCu type structure. The compound had magnetic properties suitable for a PM and a high Curie temperature. The $BH_{\max}$ of this type of magnet reached 160kJ/m^3 . In an attempt to produce compounds with even higher magnetizations, the Co content was increased to provide a higher saturation magnetization and a higher Curie temperature, followed by a compositional compromise. A high magnetic hardness was obtained by the process of precipitation

hardening. The maximum energy product was increased to 264kJ/m^3 with the addition of Fe, Cu, and Zr [135].

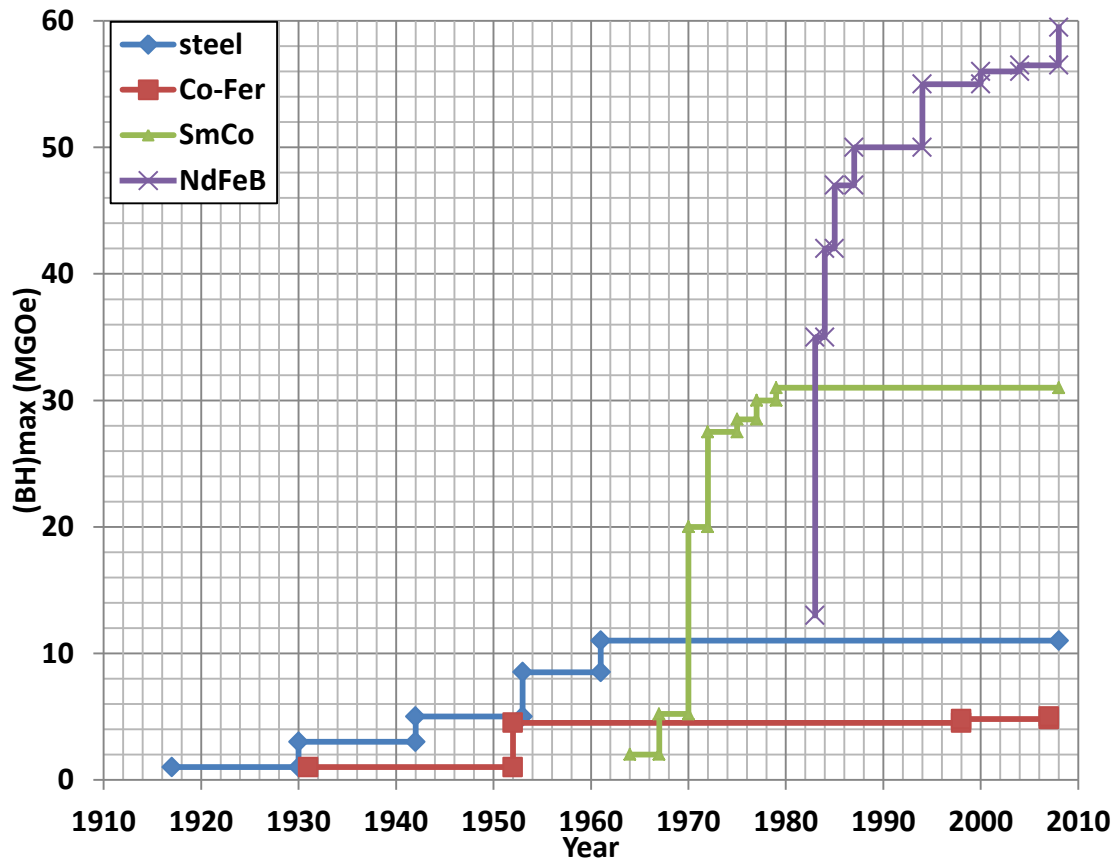


Figure 4.1: Development of PMs [134].

The high cost of Sm and Co led to new research focused on discovering a new Fe alloyed compound that was cheaper and had the same technical properties. In the mid-1980s, melt spinning and powder-metallurgy techniques led to the invention of a new important rare-earth magnet called Neodymium-Iron-Boron (NdFeB), which resulted in energy products greater than 288kJ/m^3 . These NdFeB magnets rapidly replaced SmCo types due to their superior magnetic properties and lower cost. Since then, by improving the alloy and powder preparation, the magnetic press, and the surface coating, NdFeB magnets with a BH_{max} over 430kJ/m^3 have been commercially produced [136]. The use of magnets in electrical machines has increased due to the developments in magnet features and the decrease in magnet prices.

In the recent years, there have been many studies on the development of the design and operating characteristics of electrical machines with PMs [133]. Such trends and examples were discussed by Karl J. Strnat [136]. The design aspects of PM machines

using NdBF_e magnets were presented [137]. P. Pillay and R. Krishnan made a comparison of PMSM and BDCM types, obtaining the application characteristics of these two magnets [138]. The theory and design of fractional-slot concentrated-winding synchronous PM machines and their high-power density, flux-weakening capability, comparison of single- versus double-layer windings, fault-tolerance rotor losses and parasitic effects as well as a comparison of their interior structure versus surface PM machines and various other electric machines were obtained by EL-Refaie [84].

4.2 Characteristics of PM Materials

The magnets' characteristics must be known to decide which magnet is the most suitable for different applications. Requirements demanded by applications are flux density (B_r), $BH_{\max}$, resistance to demagnetization (H_c), a good demagnetization curve, recoil permeability, corrosion resistance, electrical resistivity, a low magnetizing field requirement, a usable temperature range, magnetization change with temperature, physical strength, availability in particular size and shapes and manufacturability. Characteristics of PM materials can be classified generally under three groups as magnetic, temperature and manufacturing characteristics. These can be detailed as follow sections.

4.2.1 Magnetic properties

The basis of magnetic properties is the BH curve or hysteresis loop, which characterizes each magnet material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field. Demagnetization curve shown in Fig. 4.2, which is in the second quadrant of the BH curve, describes the conditions under which PMs are used in practice. This curve provides specific information about how a given material performs under a variety of magnetic loading and temperature conditions. The curve is representative of the specific material used to make the magnet, and is independent of the geometry the magnet is made into.

A PM has a unique, static operating point considering air-gap dimensions are fixed and any adjacent fields are held constant. Otherwise, the operating point moves

among the demagnetization curve. $BH_{\max}$ is the maximum product of the magnetic induction (B_d) and magnetizing field strength (H_d) in the demagnetization curve, and represents twice the maximum energy that can be stored in the magnetic field created in the space around a magnet of optimum shape.

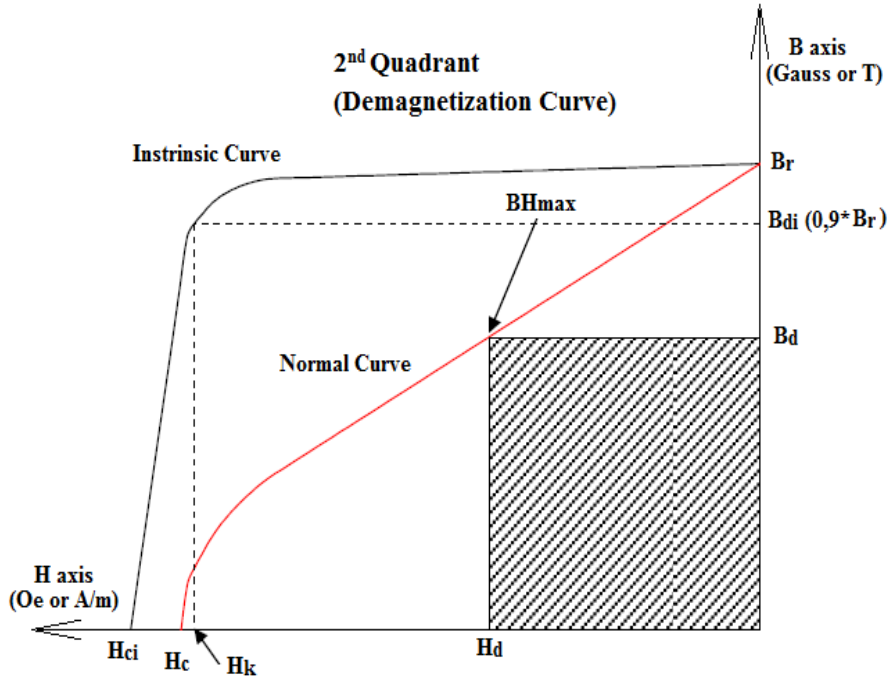


Figure 4.2: Demagnetization Curve.

There is a useable upper limit for every PM. With a straight demagnetization characteristic throughout the demagnetization curve and a recoil permeability of unity, the maximum energy-product $BH_{\max}$ can be given by (4.1) in J/m^3 [140].

$$BH_{\max} = \frac{B_r^2}{4\mu_0} \quad (4.1)$$

A PM is magnetized through the application of a strong external magnetic field. Insufficient magnetization results in substantial shortages in both B_r and H_c . Because the magnetic field intensity necessary for magnetization varies across materials, a magnetization test is conducted in advance to determine the sufficient magnetic field to be applied. PMs have been developed to achieve higher B_r , $BH_{\max}$ and greater resistance to demagnetization (greater H_c).

Generally, there is now a strong and accelerating trend toward the use of PM machines that was made possible by the progress in the PM materials field. In a

sense we are returning to the early energy conversion concepts of over one hundred years ago. This trend is strongly aided by a synergy of recent developments: in machine design (internal magnets, axial field, iron-less rotor, linear motors), in power semiconductors which now make it practical to employ new ways of motor operation (brushless with electronic commutation; often in servo loops, variable-frequency synchronous, stepper), and in electronic “motion control” with the aid of position/speed sensors and microprocessors. Another factor favoring PM motors and actuators in systems where many different motions must be independently performed is the increasing economy of using separate small motors placed where needed instead of the traditional single large machine with purely mechanical power distribution. Motors and generators are perhaps the most visible of the early electrical applications of magnets, but there are many others. Of those which also have their roots in the late 19th century, several became commercially very important and some remain so to this day, The moving coil galvanometer (d’Arsonval), long was the most common electrical measuring instrument; it has a PM circuit which initially comprised a long and bulky steel magnet.

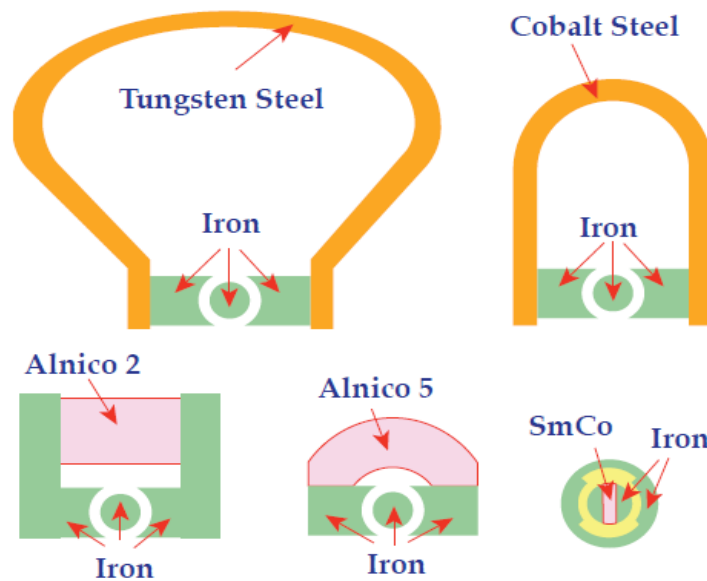


Figure 4.3: The evolution of the magnetic circuit of moving coil meters reflects the progress in magnet materials development [141].

As magnet materials improved, the magnetic circuit changed shape and the magnet shrank until it is now often just a segment of the small core inside the coil. (See Fig. 4.3). In electronic communications, telephone receivers, dynamic microphones, audio pickups and, most importantly, loudspeakers usually contain PMs.

4.2.2 Temperature properties

The major limitation in the application of magnets is the limited temperature tolerance. For PMs the BH loop changes shape with temperature. With an increase in temperature, all PMs' lose remanence.

Every magnetic material has a characteristic temperature known as the Curie temperature at which all magnetization is reduced to zero. At this temperature, thermal agitations apply more force against movement than the resistance of the magnetic domains and the domains of the magnet randomize. After the material reaches the Curie temperature throughout its bulk, it will show virtually no net magnetization, and can be treated as virgin material. While the Curie temperature is high, the magnet's operation must be limited because of the relatively high temperature coefficient of residual flux density above that temperature.

For maximum power density the product of the electric and magnetic loadings of the motor must be as high as possible. The electric loading is limited by thermal factors and the demagnetizing effect on the magnet. A high electric loading necessitates a greater magnet length in the direction of magnetization to prevent demagnetization. The greatest risk of demagnetization is at low temperatures when the remanent flux density is high and coercivity is low; in a motor, these result in the highest short-circuit current when the magnet is least able to resist the demagnetizing ampere-turns. It also necessitates a high coercivity, which may lead to more expensive grades of material (such as 2-17 cobalt-samarium), especially if high temperatures will be encountered.

4.3 Manufacture of PMs

Another important characteristic of the magnets is manufacturing. PMs are manufactured by one of the following methods:

- Sintering (all PMs),
- Pressure Bonding or Injection Molding (Rare Earths, Ceramics),
- Casting (Alnicos),
- Extruding (Bonded NdFeB),

- Calendering (NdFeB)

Table 4.1: Structural Comparison of PMs.

<i>Method</i>	<i>Properties</i>
Sintering	*+ Maximum energy product for a given magnet size & weight *– Limited to simple geometries – Brittle *➤ Maximum Output
Injection Molding	+ Complex geometries + Relatively tough + Lower assembly costs + Allows high volume manufacturing – Lower BHmax ➤ Shaping flexibility
Pressure Bonding	+ Greater volumetric loading of magnetic phase – Complex magnetizing patterns – Brittle – Tight geometric tolerances – Limited to simple geometries ➤ Low cost manufacturing
Casting	+ Allows relatively complex shapes + Higher BHmax + Extremely hard and brittle – Difficult to machine – Lower mechanical resistance ➤ Shaping flexibility
Calendering & Extruding	+ Complex geometries + Easy to tool and machine – Lower BHmax ➤ Shaping flexibility

*+ Positive *– Negative *➤ Keyword

Fully automated production processes lead to more uniform magnetic properties and repeatable precision. However, these magnets have lower magnetic properties compared to their sintered counterparts due to the polymer dilution effect. The maximum operating temperature is limited, to some extent, by the temperature characteristics or limitations of polymers leading to higher tooling costs for injection and extrusion molding processes.

4.4 PM Materials Used in Electrical Machines

Many types of electrical machines can use PMs. Many million units are produced annually, particularly for automotive applications. In cars they operate auxiliary devices like windshield wipers, blowers, cooling fans; window, seat, mirror and roof actuators; fuel and windshield washer pumps. Increasingly, starter motors also use magnets. For economic reasons, the PM material in most small motors is sintered ferrite, although bonded rare earth PM are of increasing importance.

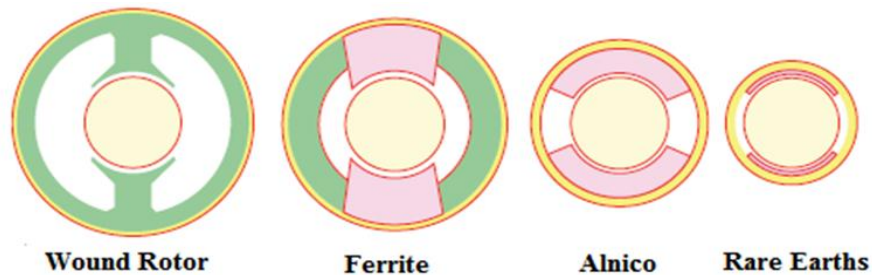


Figure 4.4: Evolution of stator magnet geometry in small DC motors. (Based on 2-pole motors of comparable power using identical wound rotors.).

When the smallest possible weight and volume are desired, as in aerospace applications, dense SmCo and NdFeB are also used. Fig. 4.4 shows how the replacement of the wound-field stator by Alnico, then the switch to anisotropic ferrite, and finally the use of rare earth PM influence the stator geometry and relative size of functionally comparable motors, here using the same wound rotor [141].

PMs are an essential part of electrical machines. With such machines energy input is necessary only for changing the energy of the magnetic field, not maintaining it. A PM can produce a magnetic field in an air gap with no excitation winding and no dissipation of electric power. The excitation combination with microprocessors and power-semiconductors makes PM materials truly attractive for application in electrical machines.

Different PM materials are used in present applications. There are three classes of PMs currently used for electric machines [147]:

- Alnicos : Al, Ni, Co, Fe;
- Ceramics (Ferrite): Barium Ferrite and Strontium;
- Rare Earth Magnets: Samarium-Cobalt (SmCo), Neodymium-Iron-Boron (NdFeB).

Basic characteristics of the PMs using in electrical machine applications are given in Table 4.2. Compared to some other magnet materials Alnico magnets have good temperature stability, are less affected by temperature changes and have a very high Curie point. The material is hard and brittle. It may have a bright, polished, chrome-like appearance or seem a dull, rough gray if ungrounded [39]. Alnico is produced by two typical methods, which are casting and sintering processes [143]. Sintering offers superior mechanical characteristics, whereas casting delivers higher energy products and allows for the design of intricate shapes. Two very common grades of Alnico magnets are 5 and 8. Chemically, the Alnicos are iron-cobalt-nickel based alloys with minor additions of aluminum and copper, and in some grades titanium. Typical compositions for today's main commercial grades are shown in Fig. 4.5.

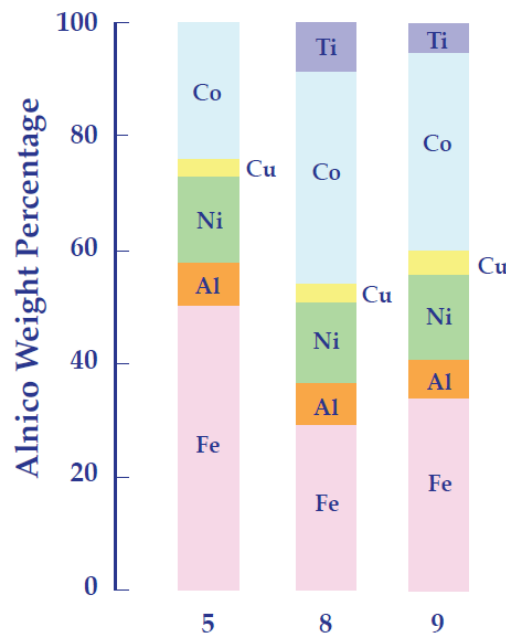


Figure 4.5: Typical compositions of important Alnico grades in the chronological order of their development [141].

Samarium cobalt is a type of rare earth magnet material that is highly resistant to oxidation, has higher magnetic strength, high remanence, high intrinsic coercivity and high corrosion resistance. Additionally, it shows very low variation of field strength with differing temperatures, has better temperature resistance than Alnico material, a very high Curie point and high corrosion resistance.

Table 4.2: Basic Characteristics of PMs.

<i>Properties</i>									
<i>PM</i>	Br (T)	Hc (kA/m)	BH _{max} (kJ/m ³)	Max. Oper. Tem. (°C)	Density (g/cm ³)	Relative Permeability (μ/μ ₀)	Electrical Resistivity (μΩ·cm)	Cost (\$/kg)	Cost Percentage
Alnico5	1.25	50.93	43.8	540	7.3	2,2	45 - 75	12-18	%23.4
Alnico8	0.83	131.3				2		18-24	
Alnico9	0.7	151.2	39.8			1,5		18-24	
SmCo24	1	708.2	191	350	8.3	1,05	80 - 90	120-150	%100
SmCo28	1.07	819.67	222.8	380				120-160	
NdFeB30	1.1	843.54	238.7	300	7.42	1,09	120 - 160	80-90	%80.5
NdFeB35	1.23	899.25	278.5		7.4			80-100	
NdFeB54	1.5	1050	437.7		7.5	1,05		100-140	
Ceramic5	0.395	190.985	28.6	300	4.98	1,05	10 - 47	5	%10
Ceramic8	0.39	254.648	27.9					8	
Ceramic10	0.42	234.753	33.4					10	

Sintered samarium cobalt magnets are brittle, prone to chipping and cracking and may fracture when exposed to thermal shock. They are also producible only in small pieces, which must be bonded together for larger assemblies. Due to the high cost of samarium, samarium cobalt magnets are used for applications where high temperature and corrosion resistance is critical. The biggest advantage of SmCo over NdFeB is better temperature stability.

Another important type of magnet is Neodymium Iron Boron (NdFeB). NdFeB with $BH_{\max}$ increased to up to $437,7\text{kJ/m}^3$ (for NdFeB54), is the latest and most powerful type in another family of rare earth magnetic materials, which is used in large machine applications. This material has similar properties as Samarium Cobalt except that it is more easily oxidized and generally doesn't have the same temperature resistance. They offer the highest possible remanence and depending grade. NdFeB magnets are highly corrosive and brittle, except in some molded and sheet forms.

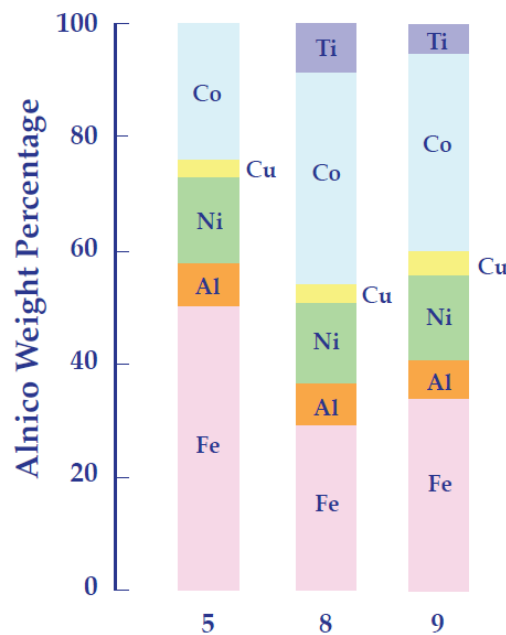


Figure 4.6: Typical compositions of commercially available Rare Earth Magnets.

The material has also been improved, with lower chemical reactivity, improved consistency, and high recommended temperatures for long-term use. Surface treatments including gold, nickel, zinc and tin plating and epoxy resin coating have been developed that allow them to be used in most applications. The trend to polymer-bond magnets is increasing with the availability of anisotropic powders

[144]. For many applications, these favorable features have made NdFeB the first choice of magnet, resulting in its widespread use. Fig. 4.6 shows the approximate compositions of several important magnet types [141]. They all contain a large weight fraction of one or more rare earth elements.

Table 4.3: General Comparison of the PMs.

PM	Positive	Negative
Alnico	• High corrosion resistance • High mechanical strength • High temperature stability	• High cost • Low coercive force • Low energy product
SmCo	• High corrosion resistance • High energy product • High temperature stability • High coercive force	• Highest cost • Low mechanical strength • Brittle
NdFeB	• Very high BHmax • High coercive force	• Higher cost • Low mechanical strength • Brittle • Moderate temperature stability • Low corrosion resistance
Ferrite	• Low price • High demagnetization resistance • Very high corrosion resistance	• Very brittle • Require expensive tooling

Hard ferrite (ceramic) magnets were developed in the 1960's as a low cost alternative to metallic magnets. Even though they exhibit low energy (compared with other PM materials) and are relatively brittle and hard, ferrite magnets have won wide acceptance due to their good resistance to demagnetization, excellent corrosion resistance and low price per pound. For lowest cost, ferrite or ceramic magnets are the universal choice. This class of magnet materials has been steadily improved and is now available with remanence of 0.42 T and almost straight demagnetization characteristic throughout the second quadrant. The temperature characteristics of ferrite magnets can be tailored to the application requirements so that maximum performance is obtained at the normal operating temperature, which may be as high as 300°C. Ferrite materials have high coercive force, but they have high shortness and complexity of processing. Also, a temperature essentially influences at magnetic

properties for such magnets. Characteristics and general comparison of magnets used in electrical machines are shown in Table 4.2 and 4.3 respectively.

Compared to other PMs, NdFeB magnets are more sensitive to temperature and special care must be taken in design for working temperatures above 100 °C. For very high temperature applications Alnico or rare-earth cobalt magnets must be used. A samarium-cobalt magnet tends to break down magnetically at 700-800 °C, the Curie temperature of most samarium-cobalt magnets, after which the material's performance will be significantly degraded. It can be recommended considering the inherently SmCo magnets for high temperature applications of low to moderate tonnage requirements. BH demagnetization and temperature curves of whole rare-earth PMs are given in Fig. 4.7 [141].

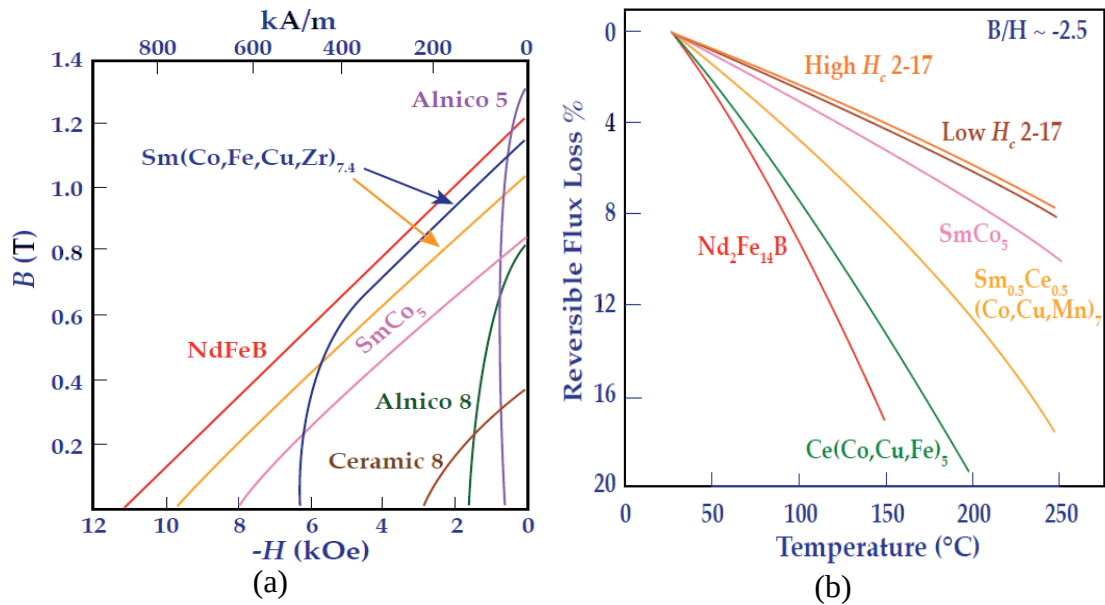


Figure 4.7: Macnetical and phsical curves of PMs ; (a) Demagnetization Curve, (b) Reversible Flux versus Temperature plots for several Rare Earth PM Materials.

Compared to SmCo, NdFeB magnets have a magnetic energy product up to a magnitude larger, high remanence and high intrinsic coercivity. These attributes are important in PM machines [145]. The focus on devices with low weight and small size has driven usage of rare earth magnets so that NdFeB magnets now represent over half of all magnet sales on a dollar basis. As an example for better demonstrating the relative magnet sizes: A NdFeB54 magnet with a volume of approximately 0.2cm³ and an Alnico5 magnet with a volume of 14.3cm³ provide same flux density (they generate 1T at 5mm from the pole face of the magnet), which

means to be able to provide the same magnetic field strength near the pole, the Alnico5 magnet should be 71.5 times larger than the NdFeB54 magnet. As seen in the example rare earth, especially NdFeB magnets should be chosen wherever small size and low weight are required. Furthermore, system size depends on the steel flux path, meaning that a larger, weaker magnet would require a larger structure that requires more steel.

4.5 Applications for PMs

Compared to PMs uses in the market, electrical machines have important application areas as seen in Fig. 4.8. PMs can be designed to be on the stator or the rotor. The magnets can be mounted on the rotor surface or embedded in the rotor. Opting for interior construction simplifies the assembly and relieves the problem of retaining the magnets against centrifugal force. It also permits the use of rectangular instead of arc-shaped magnets, and usually provides an appreciable reluctance torque which leads to a wide speed range at constant power. Use of PMs in the construction of electrical machines leads to the following benefits [39];

1. No electrical energy is absorbed by the field excitation system and thus there are no excitation losses which creates a substantial increase in efficiency,
2. Higher torque and/or output power per volume compared to electromagnetic excitation,
3. Better dynamic performance than motors with electromagnetic excitation,
4. Simplification of construction and maintenance,
5. Reduction of prices for some types of machines.

Replacing the field winding and pole structure with PMs usually permits a considerable reduction in the stator or rotor diameter, caused by the efficient use of radial space by the magnet and the elimination of field losses. In the meanwhile, field control is sacrificed by the elimination of brushes, slip rings, and field copper losses. Armature reaction is usually reduced and commutation is improved, owing to the low permeability of the magnet. The loss of field control is not as important as it would be in a larger drive since it can be overcome by the controller and in small drives the

need for field weakening is already less common. Excitation combination with power electronics makes PM motors attractive for achieving constant torque and power characteristics. Still, the cost of the magnet may be a limiting factor. The air-gap flux-density of AC motors is limited by the saturation of the stator teeth. Excessive saturation absorbs too much excitation MMF (requiring a disproportionate increase in magnet volume) or causes excessive heating due to core losses.

PMs are used in many different industrial products and for many different functions. As shown in Fig. 4.8, the worldwide use of PMs can be divided into seven main areas.

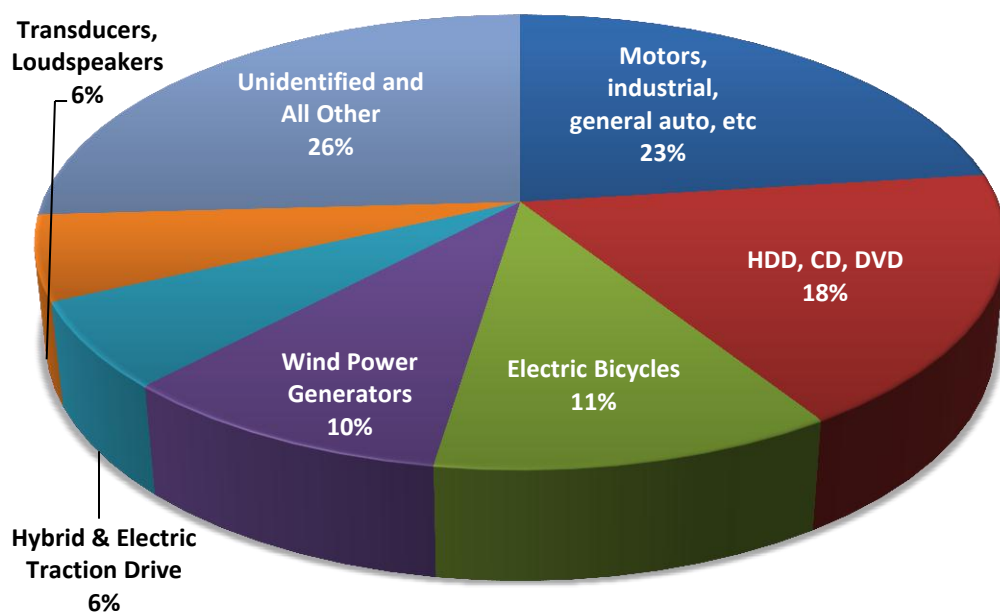


Figure 4.8: World output for Rare-earth PMs divided into uses [146].

Magnets have wide applications in Electro-Mechanical Machines and Devices. Such systems having PM's may be grouped as follows.

Electric Motors and Generators: Some fast growing applications are HDD, CD, DVD applications, Hybrid & Electric Traction Drives and wind power generators. One of the main uses for rare earth magnets, primarily NdFeB, is in electro mechanic devices such as hard disk drives, CD's and DVD's where the magnet is used both for driving the spindle motor and for positioning the read/write head. Hybrid automobiles and solely electric vehicles are becoming increasingly more common in the US and Europe. Still, the less expensive electric bike is providing more widespread mobility throughout Southeast Asia and India.

Types-DC (commutator and brushless), synchronous, hysteresis; radial or axial field (disc) motors, step motors. Brushless PM D.C. motors are widely used in computers, household and industrial products, and automobiles [149]. Axial Flux PM Brushless Motors have a high power density and are particularly suitable for electrical vehicles, pumps, fans, valve controls, centrifuges, machine tools, robots and industrial equipment. Electromechanical traction drives are used in hoists or in wind turbines as generators [150]. PM Step Motors have many applications (in watches and clocks, timer switches, cameras, flight control, etc.), computer peripherals (floppy-disc head positioners, paper and ribbon advancers and daisy-wheel rotation in printers, typewriters, and office machines of all kinds). Step motors can be in hybrid type (PM plus toothed iron wheels) and pure PM construction. The other uses are in Electric Bicycles, Wind Power Generators, Hybrid & Electric Traction Drive, Torque-coupled drives. Wind power usage is increasing rapidly and the newest generators use PMs, specifically NdFeB types [148], as these magnets are vital for reducing the size and improving the performance of magnetic circuits.

Electro-Mechanical Actuators: Linear -Force motors for valves, etc.; printer hammer mechanisms; computer disc-drive head actuators (VCM); laser focusing and tracking (optic/magneto optic recording; audio CDs, video, data); recorder pen positioners, rotary-Disc drives VCMs; aircraft control surface actuators; material handling robots.

Measuring Instruments and Electric Current Control: PMs are used not only in electric motors and generators, but also in devices such as slim-profile speakers used in mobile phones and in medical equipment such as MRI machines, energy storage systems, pipe inspection systems etc. [146-149]. Even though the volume of magnet used per device is small, the huge quantities of devices require a large amount of magnets. Moving-coil and moving-magnet meters for many functions, gauges. Circuit breakers, reed switches, miniature biased relays, thermostats, automotive ignition, eddy current motors' over speed switches, arc blow-out magnets, magnetic braking, relays and switches, magnetic separation.

The magnetic loading, or air-gap flux, is directly proportional to the remanent flux density of the magnet, and is nearly proportional to its pole face area. A high power density therefore requires the largest possible magnet volume (length times pole area). These motors have the disadvantage of high cost compared to conventional motors since it is necessary to include power electronics.

For economic reasons, the PM material in most small motors is sintered ferrite, although bonded rare earth PM are of increasing importance. When the smallest possible weight and volume are desired, as in aerospace applications, dense SmCo and NdFeB can be chosen.

4.6 PM Market

China produces 97% of the world's rare earth elements, a key component in a large assortment of advanced military and civilian technologies. Increasing global demand and export quota reductions by the Chinese over the past six years have led to international concerns about future supply shortages [139]. Therefore, in the design of the electrical machines, the selection of the appropriate materials and the proper design of the machine with all its components including magnets are crucial.

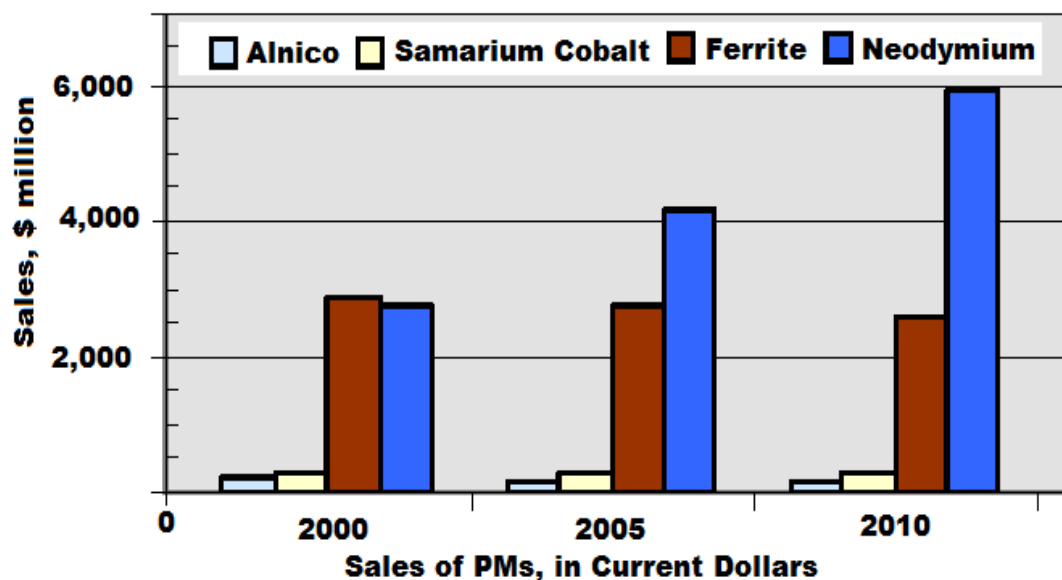


Figure 4.9: Global Magnet Sales [146].

Increasing use in electric vehicles and wind power are placing extraordinary demands on material supply and magnet performance. As demand is poised to skyrocket, anxiety over the possibility of China reducing export quotas has increased calls for the development of alternative technologies and recycling of rare earth materials. An additional approach to ease this problem is increasing the performance of today's rare earth magnets.

The PM market includes data that is readily available as well as data which is difficult to obtain or not credible for magnetic materials. In Fig. 4.9, the presented

information is based on readily available market data. As can be seen in the figure, sales in current dollars are increasing exponentially. According to the figure, ferrite continues to be widely used, primarily due to its low cost and wide availability. In 2005, sales of all PMs were only \$8 billion. According to some future sale estimates, NdFeB alone could account for sales over \$17 billion by 2020 – that is, assuming adequate supplies of the raw materials [146]. Although sales of Ferrite magnets may seem high, their usage in the electrical machines with large power densities is not preferred because of Ferrite magnets' small BHmax value (41.4 kJ/m^3).

5. IMPLEMENTATION of FRACTIONAL SLOT CONCENTRATED WINDING TECHNIQUE to LARGE SALIENT-POLE SYNCHRONOUS GENERATORS

In this section, analytical expressions including winding factor, resistance, inductance and flux leakage of the concentrated windings are given. How it may achieve using PMs between the adjacent pole shoes and which methods of analysis used are explained. In the following sections, calculation of EMF, magnetic field density, terminal voltage, harmonics, THDs, losses, slot ripples and efficiency of the FSCW machines are expressed.

5.1 Calculations of Winding Parameters

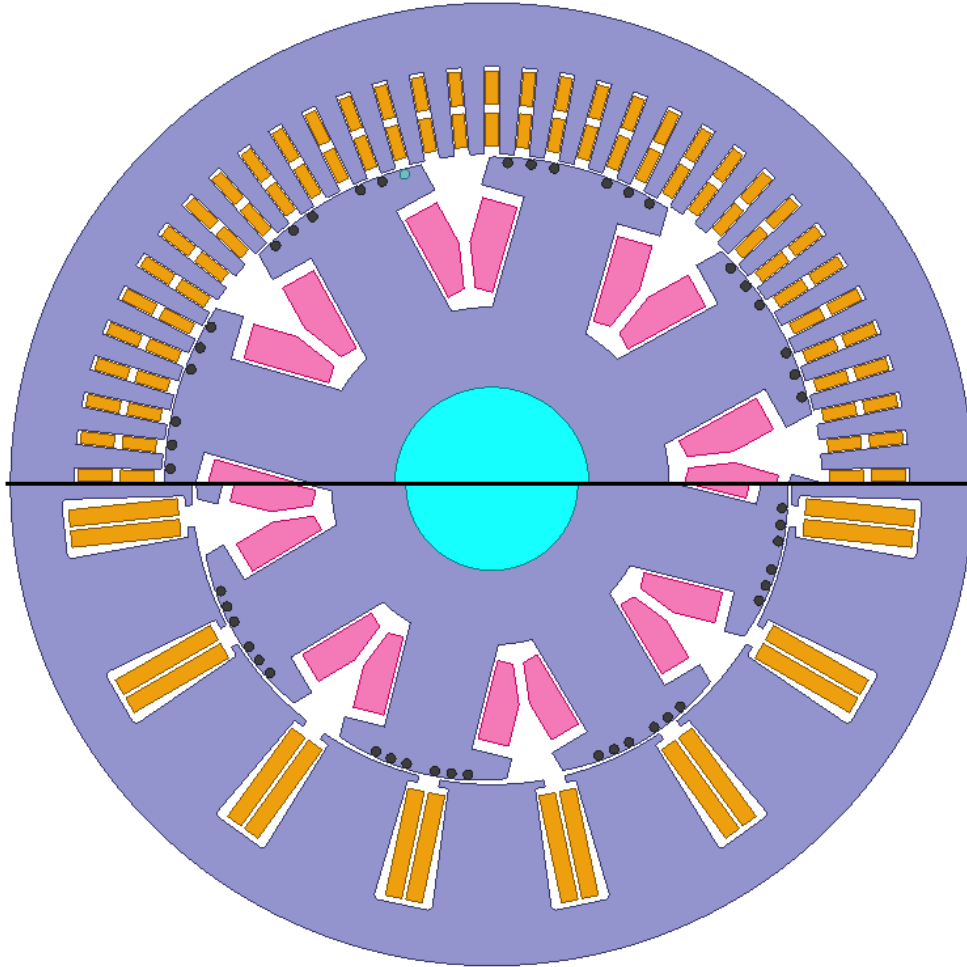
The phase windings of electrical machines are series or parallel connected by winding element sets. Each winding element set is series connected by neighbor windings (also known as winding element). As an example; 69 slots, 8 poles and 15 slots, 8 poles structures of 3-phase overlapping (conventional-distributed) windings and non-overlapping (fractional-concentrated) winding configurations are shown in Fig. 5.1. In distributed windings, the coil pitch can be short or long pitched depending on the number of slots and poles. In concentrated windings, one winding element is inserted in two neighbor slots. In other words, the winding element is around one tooth. Then stator teeth and winding elements have the same number. Comparison of overlapping and non-overlapping windings may be summarized by itemizing as follows:

- 1) To obtain symmetrical EMF of non-overlapping windings, the slot number should be multiples of m . And the structure of non-overlapping windings cannot be full pitch.
- 2) The pitch factor can be designed to eliminate a special order of EMF harmonic. In distributed windings, the order of EMF harmonic can be an

arbitrary odd number. While in non-overlapping windings, the order of EMF harmonic only can be an m or multiple of phase number.

- 3) In non-overlapping windings, the efforts of slot width on the EMF harmonics cannot be ignored. Choosing suitable slot width can eliminate a special order of EMF harmonic.

69 slots-8 poles double-layer distributed winding configuration



15 slots-8 poles double layer concentrated winding configuration

Figure 5.1 : Comparison of fractional-slot concentrated and distributed full-pitch windings.

5.1.1 Calculation of winding factors for SPSGs

In some synchronous machine stator windings, short pitched coils (the distance between two sides of coil is smaller than that between two adjacent magnetic poles) are used to eliminate a certain harmonic, and the fundamental component of the resultant magneto-motive force (MMF) created by the stator currents of a synchronous machine with conventional windings is given by (5.1).

$$F = \frac{4}{\pi} \frac{k_{wh} N_{ph}}{P} i_a \cos \theta \quad (5.1)$$

where N_{ph} is the total number of turns of the phase winding, which is formed by these coils, P is the number of poles, i_a is the peak value of the phase current, θ is the current angle (θ is equal to zero for q -axis current only), and k_{swh} is the winding factor including h order harmonic which is given in (5.2).

$$k_{wh} = k_{ph} k_{dh} k_{swh} \quad (5.2)$$

where k_{ph} is known as the pitching factor with h order harmonic, k_{dh} with h order harmonic is known as the distribution factor of the winding and k_{sw} is the skewing factor, and they can be calculated as (5.3a), respectively. By simplifying the (5.3a), the winding factor for FSCW machine given in (5.3b) has been obtained. Winding factor calculation of CSDW machine is same as FSCW machine except for k_{dh} . For accurate calculation of k_{dh} coefficient of CSDW machine, (5.3c) should be used.

$$k_{ph} = \sin\left(h \frac{\pi \tau_c}{2\tau_p}\right), \quad \tau_c = \frac{\pi D_c}{Q}, \quad \tau_p = \frac{\pi D_p}{P}, \quad k_{ph} = \sin\left(h \frac{\pi P D_c}{2Q D_p}\right),$$

$$k_{dh} = \frac{\sin\left(h \frac{\pi}{2m}\right)}{q \sin\left(h \frac{\tau_c}{2}\right)}, \quad q = \frac{Q}{Pm}, \quad k_{dh} = \frac{Pm}{Q} \sin\left(h \frac{\pi}{2m}\right) \left[\sin\left(h \frac{\tau_c}{2}\right)\right]^{-1}, \quad (5.3a)$$

$$k_{swh} = \frac{\sin\left(h \frac{P\gamma}{4}\right)}{h \frac{P\gamma}{4}}, \quad \gamma = \frac{2\pi}{Q}, \quad k_{swh} = \frac{2Q}{hP\pi} \sin\left(h \frac{P\pi}{2Q}\right)$$

$$k_{wh} = \frac{2m}{h\pi} \sin\left(h \frac{\pi P D_c}{2Q D_p}\right) \sin\left(h \frac{P\pi}{2Q}\right) \sin\left(h \frac{\pi}{2m}\right) \left[\sin\left(h \frac{\tau_c}{2}\right)\right]^{-1} \quad (5.3b)$$

$$k_{dh(c)} = \frac{Pm}{Q} \sin\left(h \frac{\pi}{2m}\right) \left[\sin\left(h \frac{P\pi}{2Q}\right)\right]^{-1} \quad (5.3c)$$

where τ_c is the stator coil pitch and τ_p is the pole pitch as shown in Fig. 5.2, q is the number of slots per pole per phase, m is the phase number, γ is the skew angle which is the angle between the first lamination's slot and its corresponding slot in the last lamination along the axial direction (mechanical angle in radians), Q is the number of slots, D_c and D_p are average diameters of stator and rotor, respectively. As it know as well, the winding type of an electrical machine is mainly determined by the

number of q . The distribution factor decreases as the number of slots increases and it is the ratio of the phase EMF for a distributed winding to that for a concentrated one. Due to reduction techniques [151-153] often contribute to a machine with weaker performance; skewing method can be used for reduction the cogging torque in two teeth which leading to a reduction of spatial harmonics of the generator's output variables. Furthermore, $k_{wh}N_{ph}$ is known as the effective number of turns of the phase winding. On the other hand, the MMF of a SPSG with FSCWs is given by;

$$F = \frac{4}{\pi} k_{wh} n_l N_{ph} Q B_{\delta a} A_{\delta} i_a \cos \theta \quad (5.4)$$

where n_l is the number of layers in each slot, $B_{\delta a}$ is the peak value of the fundamental no-load air-gap flux density, and A_{δ} is the air-gap area. The winding factor is proportional to the MMF as seen in (5.4). According to (5.4), to be able to design compact and high efficiency synchronous machines, winding factor should be as high as possible. Because, higher current or more number of turns are required in an electrical machine with a low winding factor in order to provide the same MMF. As a result of low winding factor, copper losses, total dimensions, weights and also cost of the machine increase and so efficiency decreases. On the other hand, high winding factors cause higher harmonic order. This is very important for design of a generator. Optimal winding factor should be chosen for a good sinusoidal output voltage of the FSCW generator taking account the $q < 1$.

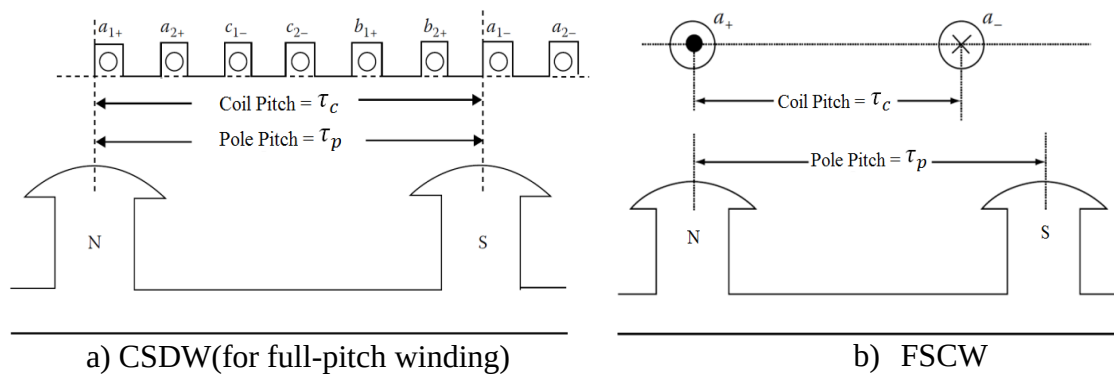


Figure 5.2 : Comparison of coil and pole pitch of conventional and FSCW SPSGs.

The winding layout of the machines shown in Fig. 5.1 is shown in Fig. 5.2. The coil pitch for a single-layer winding is equal to slot pitch as shown in Fig. 5.2 a) and longer than the coil pitch for a double-layer winding.

5.1.2 Winding factors & the q value

In the literature, the term “fractional-slot” refers to stator windings with q values less than one, and there are several q values determining the characteristics of FSCW machines [7,9,154,155]. Selecting the q value for SPSG is very important in terms of machine performance. q value in the SPSGs is limited according to PM synchronous machine. Because, in the SPSG, the P number cannot be greater than Q number for some lack of enough space for the poles and low k_{wh} value reasons. Choosing the preferred q value depends on; k_{wh} , P , Q , n_l and machine’s symmetry as seen in (5.4). Selecting the P and Q numbers as high as possible is reduced value of the total harmonic distortion (THD). This leads to an increase in cogging torque frequency and a decrease its magnitude. Product of the P and Q indicating machine’s symmetry should be an even number for low net radial force on the machine. n_l must be compatible with q value.

Table 5.1 : Fundamental winding factors for double-layer concentrated windings

$Q \setminus P$	4	6	8	10	12	14	16
6	0.866 ¹	•	•	•	•	•	•
	<i>0.866²</i>	•	<i>0.866</i>	<i>0.5</i>	•	<i>0.5</i>	<i>0.866</i>
9	0.617	0.866	0.945	0.945	0.764	0.473	0.175
	<i>0.617</i>	<i>0.866</i>	<i>0.945</i>	<i>0.945</i>	<i>0.866</i>	<i>0.617</i>	<i>0.328</i>
12	•	•	0.866	0.933	•	0.933	0.866
	<i><u>1</u>³</i>	•	<i>0.866</i>	<i>0.966</i>	•	<i>0.966</i>	<i>0.866</i>
15	•	0.481	0.621	0.866	0.906	0.951	0.951
	<i>0.951</i>	•	<i>0.711</i>	<i>0.866</i>	•	<i>0.951</i>	<i>0.951</i>
18	•	•	0.543	0.647	0.866	0.902	0.931
	<i>0.945</i>	<i><u>1</u></i>	<i>0.617</i>	<i>0.735</i>	<i>0.866</i>	<i>0.902</i>	<i>0.945</i>
21	•	•	0.468	0.565	0.521	0.866	0.851
	<i>0.953</i>	•	<i>0.538</i>	<i>0.65</i>	•	<i>0.866</i>	<i>0.89</i>
24	•	•	•	0.463	•	0.76	0.866
	<i><u>0.966</u></i>	•	<i><u>1</u></i>	<i>0.588</i>	•	<i>0.766</i>	<i>0.866</i>

• Unbalanced winding.

¹ Calculated by Magnussen [7].

² Calculated for FSCW machine using (5.3).

³ Integer-slot winding.

First rows of the each column are indicated the fundamental winding factors calculated by Magnussen [7], second rows of the each column (italic and shaded) are indicated the calculated fundamental winding factor using (5.3). In this study, the

winding factor is developed by experimental combination of pitch and distribution factors. As an example, the q value of is chosen as 0.625. A double-layer, 15 slots, 8 poles, 2.4MVA FSCW SPSG was designed and the winding factor given as bold in Table 1 was recalculated with (3). Single-layer stator winding has advantageous in terms of production according to double-layer stator winding. Although easily reproducible, single-layer stator winding has higher THD value than double-layer stator windings. Fundamental winding factors for single-layer and double-layer concentrated winding for different combinations of pole numbers P and slot numbers Q are given in Table 5.1 [7]. As it figured out from the Table 5.1, usually the winding factor (k_{wh}) increases with P and Q number. However, it is possible to increase the k_{wh} by varying the slot pitch factor (k_{ph}) and/or distribution factor (k_{dh}). In this study, k_{wh} is developed by experimental combination of k_{dh} and k_{ph} . As an example, q value of conventional SPSG is chosen 2.875 and FSCW SPSG is chosen as 0.625. A double-layer, 15Q, 8P, 2.4MVA FSCW SPSG was designed and compared with double-layer, 69Q, 8P, 2.4MVA conventional SPSG and the k_w given as bold in Table 5.1. was increased by changing the k_{ph} value.

5.1.3 Machine inductances and flux linkages

Using the winding function theory, self-inductance of phase “a” (L_{aa}), “b” (L_{bb}) and the mutual inductance (L_{ab}) between any winding “a” and “b” in any salient-pole machine (assuming that the permeance of the iron core is infinite) is given by the following equation [156, 157]:

$$\begin{aligned}
 L_{ab}(\theta) &= \mu_0 r_g l_{eff} \int_0^{2\pi} w_A(\varphi, \theta) w_B(\varphi, \theta) g^{-1}(\varphi, \theta) d\varphi \\
 L_{aa}(\theta) &= \mu_0 r_g l_{eff} \int_0^{2\pi} w_A^2(\varphi, \theta) g^{-1}(\varphi, \theta) d\varphi \\
 L_{bb}(\theta) &= \mu_0 r_g l_{eff} \int_0^{2\pi} w_B^2(\varphi, \theta) g^{-1}(\varphi, \theta) d\varphi
 \end{aligned} \tag{5.5}$$

The d -axis inductance (L_d) is calculated as given in (5.6).

$$L_d(\theta) = L_{aa}(\theta) + L_{ab}(\theta) \tag{5.6}$$

where μ_0 is the permeability of free space, r_g the average radius of the air-gap, l is the axial active length of the machine. And w_A and w_B are the winding functions of the windings “a” and “b” respectively and they all depend on the φ along the inner surface of the stator and the θ the angle which is the angular position of the rotor with respect to the stator reference axis as it seen in Fig. 5.3. The winding function $w_A(\varphi, \theta)$ represents the MMF distribution along the air-gap for a unit current flowing in the winding “a”. The winding function of a concentrated coil “a” (w_A) and coil “b” (w_B) can be expressed as in (5.7) [158-160].

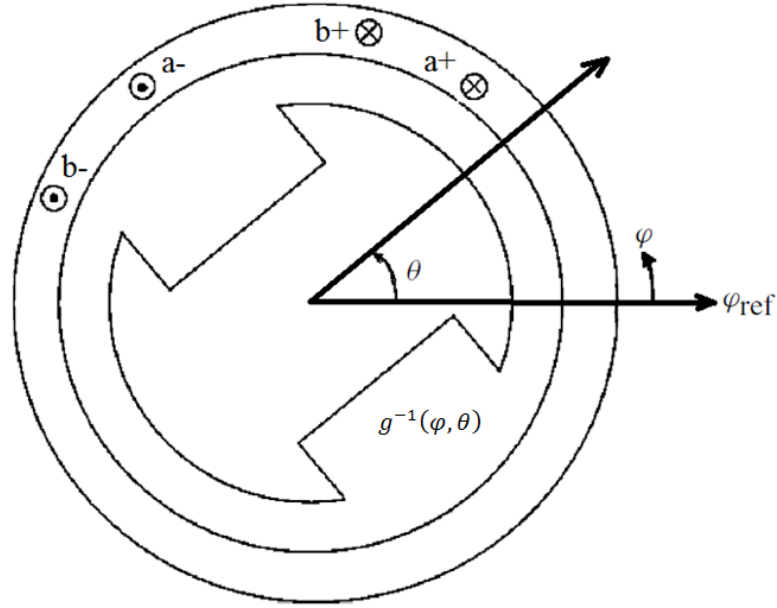


Figure 5.3 : Elementary SPSG.

$$w_A(\varphi, \theta) = \begin{cases} -\frac{\tau_{pa}}{2\pi} N_a, & 0 < \varphi < \varphi_{a+} \\ \frac{2\pi - \tau_{pa}}{2\pi} N_a, & \varphi_{a+} < \varphi < \varphi_{a-} \\ -\frac{\tau_{pa}}{2\pi} N_a, & \varphi_{a-} < \varphi < 2\pi \end{cases} \quad (5.7)$$

$$w_B(\varphi, \theta) = \begin{cases} 0, & 0 < \varphi < \varphi_{b+} \\ N_b, & \varphi_{b+} < \varphi < \varphi_{b-} \\ 0, & \varphi_{b-} < \varphi < 2\pi \end{cases}$$

where N is turn number of the related coil, τ_{pa} is the pole pitch in mechanical degrees and φ_{a+} angle for $a+$ coil side according to reference and has φ_{a-} for $a-$ coil side according to reference along the entire inner surface of the stator. The inverse air-gap length which is given in (5.5) is a function of pole shape (dynamic air-gap

eccentricity) and it determines the inductances of the salient-pole. The inverse air-gap function (g^{-1}) including dynamic air-gap eccentricity can be expressed as (5.8).

$$g^{-1}(\varphi, \theta) = \langle g^{-1} \rangle + \sum_{j=1}^{\infty} G_j \cos(j(\varphi - \theta + \lambda)) \quad (5.8)$$

where ($j = P \times \text{even harmonics}$) for non-eccentric air-gaps and ($j = \text{all harmonics}$) for eccentric air-gaps, P is the number of pole pairs, λ is the inverse gap function phase shift with respect to the selected reference axis on the stator.

Slot leakage component of the inductance should be taken account because of the significantly large stator slots. Also, the slot leakage inductance can account for more than 50% of the total inductance of machines equipped with concentrated windings. In FSCW machines, the phase inductance is generally dominated by the slot leakage component and not the air-gap component, especially for large effective air-gaps. This is primarily caused by the increase of the cross-slot leakage component, although as the effective air-gap is reduced, the air-gap component becomes more important. In addition to these, for more accurate estimate of the slot leakage 2D model that accounts for the effect of the air-gap should be used. The slot leakage inductance can be calculated using permeance functions as follows [161-165].

$$\Lambda_s = \mu_0 \left(\frac{Hs_2}{3Bs_2} + \frac{Hs_0}{Bs_0} \right) \quad (5.9)$$

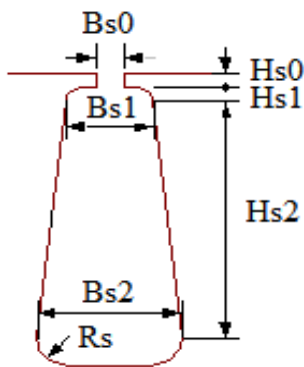


Figure 5.4 : Stator slot parameters.

where Λ_s is the specific slot permeance [H/m], and the other parameters are given in Fig. 5.4. The resultant expression for the slot leakage inductance per slot may be given as (5.10).

$$L_{slot} = n_{cond}^2 l_{eff} \Lambda_s \quad (5.10)$$

Where n_{cond} is the number of conductors per slot. Machines in which alternate teeth are wound have a significantly higher self-inductance, due to the higher harmonics and slot leakage components. They have a significantly lower mutual inductance,

which will be evident that slot opening geometry has a noticeable effect on the inductance, which becomes more significant as the effective air-gap length is increased. Assuming the air-gap field is homogeneous, magnetic flux flowing on the pole body is $\Phi_s = \Lambda_s H_b l_{eff}$, where H_b is the magnetic field intensity. While the specific slot permeance is increase, slot leakage inductance and also reactance will be increase. Furthermore, while leakage fluxes increase, the magnetic field density of the pole body (B_b) will be decrease according to $B_b = \mu_r H_b$ and also pole body magnetic field intensity (H_b) will decrease. As a result, Φ_s will remain approximately constant. Eventually, even if the leakage flux increases, the induced EMF given in (5.26) will not decrease. This significant development will lead to decrease in the dimensions of the machine preventing the saturation of the pole bodies without decreasing the output voltage.

Winding functions can be used to calculate the synchronous inductance component as well as the harmonic leakage component [115].

In order to make comparison, winding functions for a 69-slot/8-pole machine having an overlapping distributed winding with all teeth wound (N_2 turns/coil) and a 15-slot/8-pole (i.e. 5/8 slot/pole/phase) machine having a non-overlapping concentrated winding with all the teeth carry a coil (N_1 turns/coil) are considered.

The flux linkage of the FSCW machine's ($q=5/8$) winding machine in which all the teeth carry a coil is calculated from [37] as it given in (5.10a),

$$\Psi_1 = 2r_g l_{eff} \int_0^{\theta_1} N_1 B_{max} \sin(p\theta) d\theta = 2r_g l_{eff} k_{wh1} N_1 B_{max} \quad (5.10a)$$

whilst the magnetic flux-linkage of the CSDW machine's ($q=23/8$) winding machine is calculated from [37] as it given in (5.10b).

$$\Psi_2 = 2pr_g l_{eff} \int_0^{\theta_2} \frac{N_2}{2} B_{max} \sin(p\theta) d\theta = r_g l_{eff} k_{wh2} N_2 B_{max} \quad (5.10b)$$

5.1.4 Machine resistances

In an electrical machine, accurate calculation of the winding resistance depends on the correct calculation of the average length of the winding. The lengths of the

winding end turns vary as the turns move further away from the tooth wall. General view and geometric assumptions used in the end-turn length calculation for double-layer stator winding are illustrated in Fig. 5.5. While the outermost turn is assumed to have a semi-circular end turn width τ_{ss} in stator τ_{sr} in rotor, the innermost turn is assumed to have a straight end turn for both stator and rotor. τ_{ss} and τ_{sr} are the slot pitch of stator and rotor respectively.

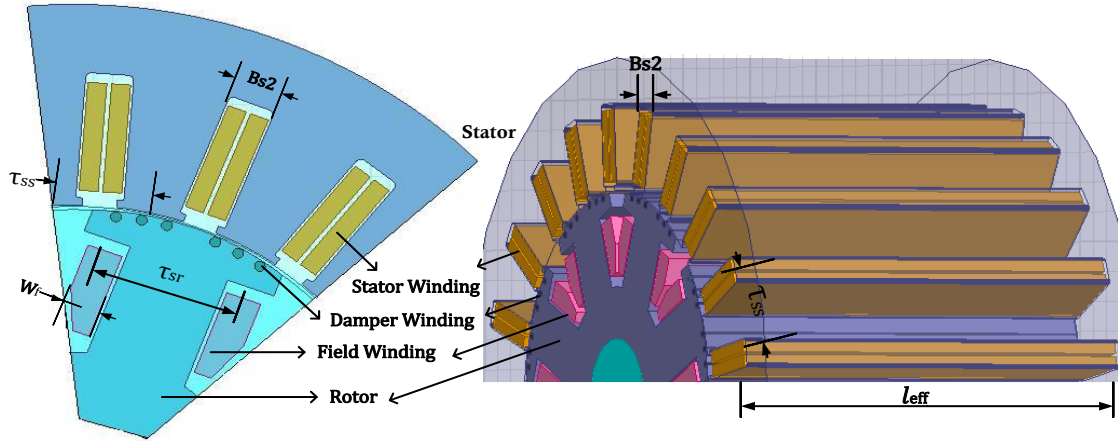


Figure 5.5 : General view and details of double-layer stator winding and field winding.

Average turn length of stator winding and field winding can be calculated approximately neglecting the wire wraps as in (5.11) respectively.

$$\begin{aligned} l_{trn,avgs} &\approx 2(l_{eff} + l_{end,avgs}) \\ l_{trn,avgr} &\approx 2(l_{eff} + l_{end,avgr}) \end{aligned} \quad (5.11)$$

where $l_{end,avgs}$ and $l_{end,avgr}$ are the average end turn lengths expressed as in (5.12).

$$\begin{aligned} l_{end,avgs} &\approx \frac{1}{2} \left(Bs_2 + \frac{\pi \tau_{ss}}{2} \right) \\ l_{end,avgr} &\approx W_f + \frac{\pi \tau_{sr}}{2} \end{aligned} \quad (5.12)$$

where W_f are stator winding and field winding width, respectively as is seen in Fig. 5.5. Finally, the resistance of the stator winding (R_{AC}) carrying AC per phase and the resistance of the filed winding (R_R) carrying DC can be calculated as (5.13). The

resistance of the damper winding can be also calculated from (5.13), but generally it is neglected compared to stator and rotor winding resistances.

$$R_{AC} = k_R \frac{N l_{end,avgs}}{\sigma S_c} \quad (5.13)$$

$$R_R = \frac{N l_{end,avgr}}{\sigma S_c}$$

where k_R is the skin effect factor for the resistance, N is the number of turns, l_{av} is the average length of a turn, S_c is the cross-sectional area of the conductor and σ is the specific conductivity of the conductor. Skin effect factor is known as the resistance factor which is the ratio of the AC and DC resistances of a conductor. Assuming the temperature to be same everywhere in the conductor, the resistances are proportional to the conductor lengths. Denoting the equivalent length of the iron core as l' , and neglecting the skin effect in end windings because the skin effect in slots is notably higher than in the end winding, then the resistance factor is [26];

$$k_R = 1 + \frac{2l'}{l_{av}} \left(\sqrt{\frac{\rho}{\pi f \mu_0 \mu_r}} - 1 \right) \quad (5.14)$$

where ρ is the resistivity and μ_r is the permeability of the conductor respectively and $\mu_0 \mu_r$ the absolute magnetic permeability ($\mu_0 = 4\pi 10^{-7} \text{ Hm}^{-1}$).

5.2 Development Method

For development of the FSCW generator placed PMs between the adjacent pole shoes are used as it seen in the cross section of aPM-FSCW SPSG shown in Fig. 5.6. The main porpoise of the PMs are not to help to increase the excitation; they mainly used for produce fluxes reversed to main fluxes flowing on each pole body which enables to prevent the saturation of the pole body.

Nevertheless, the terminal voltage of the generator will increase because of the position (polarization direction) of PMs (see Fig. 5.7). Using this saturation reduction method, output parameters of the generators such as terminal voltage, output power and loading capacity may be increased or the dimensions of the generator may be

decreased without changing the output voltage and power. In this study, the dimensions of the FSCW generator are decreased instead of increasing the output variables to be able to achieve the highest efficiency.

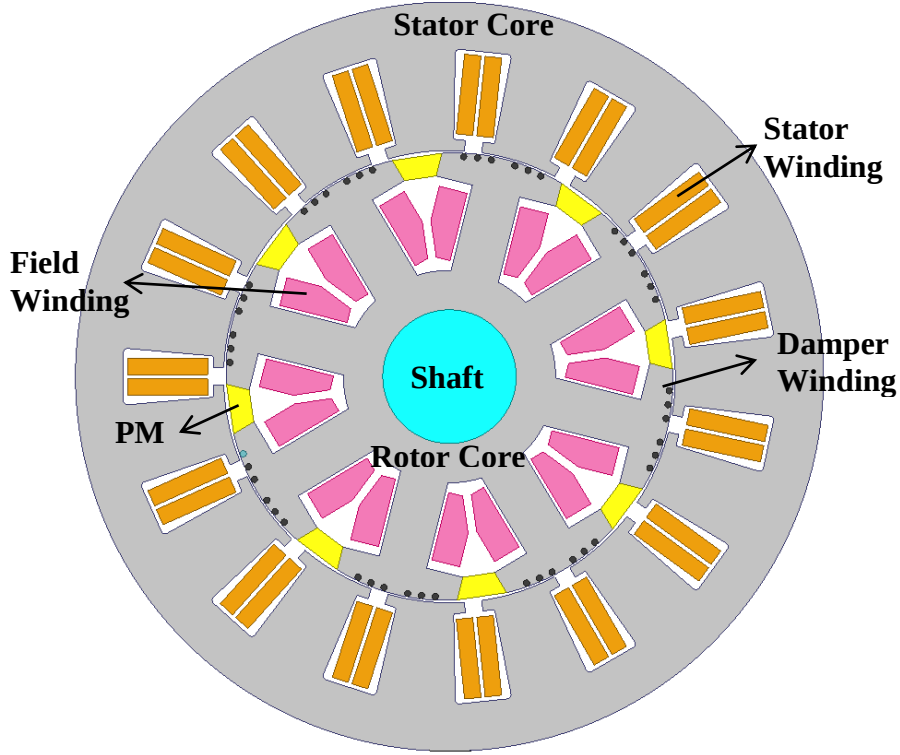


Figure 5.6 : Cross section of FSCW SPSG optimized by PMs.

5.2.1 Principle of reducing magnetic saturation

In the developed model of FSCW machine, the excitation is provided by the armature current, which can be removed, and the PMs, which provide a constant source of excitation.

The PMs are placed between the adjacent pole-shoes as it seen in the cross section of aPM-FSCW SPSG shown in Fig. 5.6. The north and south poles of the PMs face the north and south field poles, respectively as it seen in Fig. 5.7 and 5.8. The PMs are located in the leakage flux paths, not in the main flux paths produced by the armature and field MMFs. Under no-load conditions, the fluxes ϕ_m are produced by the PMs and the fluxes ϕ_f are produced by the field current I_f as shown in Fig. 5.7. The directions of ϕ_m and ϕ_f are opposite in the field poles but same in the stator tooth and yokes. Therefore, the PM fluxes ϕ_m decrease the magnetic saturation in the field pole bodies due to the field fluxes ϕ_f and hence increase terminal voltage.

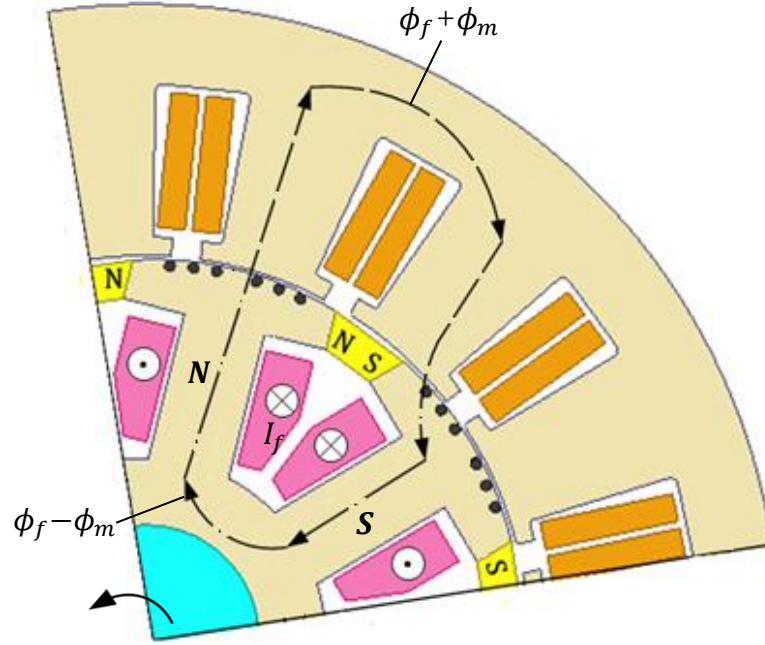


Figure 5.7 : Flux directions generated by I_f , and PMs under no-load condition.

Under load conditions, magnetic saturation arises in the pole-shoes in addition to the pole-bodies because of the main flux ($\phi_f + \phi_a$) without effect of the produced fluxes by PMs.

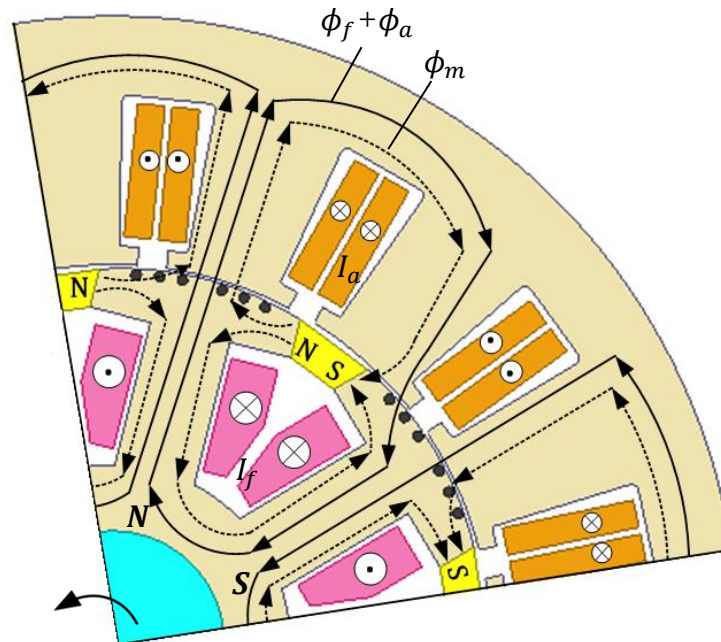


Figure 5.8 : Flux directions generated by I_f , I_a and PMs under full-load condition.

As it shown in Fig. 5.8, the PM fluxes are generated in the same direction with the fluxes created by the field current I_f and the armature current I_a in the stator-yokes while the PM fluxes are generated in directions opposite to the fluxes produced by

the field current in the pole-bodies. Eventually, the magnetic saturation in the pole bodies is reduced, on the other hand a higher electromotive force (increased by ϕ_m) is induced in the armature winding [116].

5.2.2 Analysis methods

In this study, the mechanism of reducing magnetic saturation by FSCW technique is investigated by using both the simple nonlinear magnetic circuit and the FEM at first. Simple nonlinear magnetic circuit model well known in the literature [22-27] is developed to predict the electromagnetic performance. Then, the development of the designed FSCW machine is made by additional PMs between the pole-bodies and it is investigated by using frozen permeability technique. The frozen permeability technique with FEM can be used as a method of apportioning flux-linkage contributions to the phase currents and PMs, and for inductance calculations [28-33]. In addition to these analysis method, an another analytical approach based on a 2D analytical technique for calculating the magnetic field produced by the windings of any 3-phase ac machine is adopted instead of classical 1D analytical techniques including dq , complex vector and ac phasor techniques, due to the large air-gap area of the FSCW SPSG would lead to a significant error in the magnetic field calculation [28].

5.2.2.1 Calculation of magnetic field

Choosing the optimum slot-per-phase-per-pole value, which is the first step of the design approach, to achieve lighter, cheaper and high-efficiency SPSGs with more simple structure and poles with high permeability without reducing the output power using FSCW technique is very important for determination of the characteristics of the designed machine.

The second step is to choose the accurate analysis method. Winding distribution of the FSCW machines is very different from conventional SPSG, this result in deviations from a standard sinusoidal distribution. And also, the large air-gap area of the SPSG would lead to a significant error in the magnetic field calculation.

Furthermore, such methods like phasor diagram assume the magnet flux remains constant at the open-circuit value when in fact it varies according to load. Therefore, classical 1D analytical techniques including dq , complex vector and ac phasor

techniques which require a sinusoidal winding distribution cannot be used for FSCW SPSM analysis with high precision due to their much larger effective air-gap and also armature leakage reactance. Consequently, an another analytical approach based on a 2D analytical technique for calculating the magnetic field produced by the windings of any 3-phase ac machine is adopted for FSCW SPSG [28]. Magnetic field of the stator windings which is product of some winding and slot factors, harmonic components and speed of the machine can be calculated as (5.15) [28].

$$B_{winding}(\alpha, r, t) = \frac{3\mu_0 i_a N_{ph}}{g\pi} \sum_h \frac{1}{h} k_{so} k_{dp} Fv(r) \sin[Pw_r t \mp h\alpha + \theta] \quad (5.15)$$

where, the inverse air-gap length is a function of pole shape (dynamic air-gap eccentricity) and it determines the inductances of the salient-pole. If the slot-opening is very small, i.e., $b_0 \rightarrow 0$ then the slot opening factor given by (5.16) approaches unity $k_{so} \rightarrow 1$.

$$k_{so} = \frac{2R_s}{hb_0} \sin\left(h \frac{b_0}{2R_s}\right) \quad (5.16)$$

k_{dp} is winding factor without effect of skewing factor and it is given by (5.17).

$$k_{dp} = \frac{\sin\left(h \frac{\pi}{2m}\right)}{q \sin\left(h \frac{\tau_c}{2}\right)} \sin\left(h \frac{\pi\tau_c}{2\tau_p}\right) \quad (5.17)$$

$Fv(r)$ is a function depend on the radius and the harmonic order, $\alpha = 0$ corresponds to the axis of the phase “a” winding, whose current is zero at $t = 0$. Magnetic field produced by the phase “a” winding (5.15) is applicable to any variable speed ac machine.

5.2.2.2 Frozen permeability

Using the FE simulations, individual contributions of the current and PMs to the total flux-linkage can be calculated by freezing the permeability via frozen permeability method. The flux-linkage is determined from the magnetic vector potential.

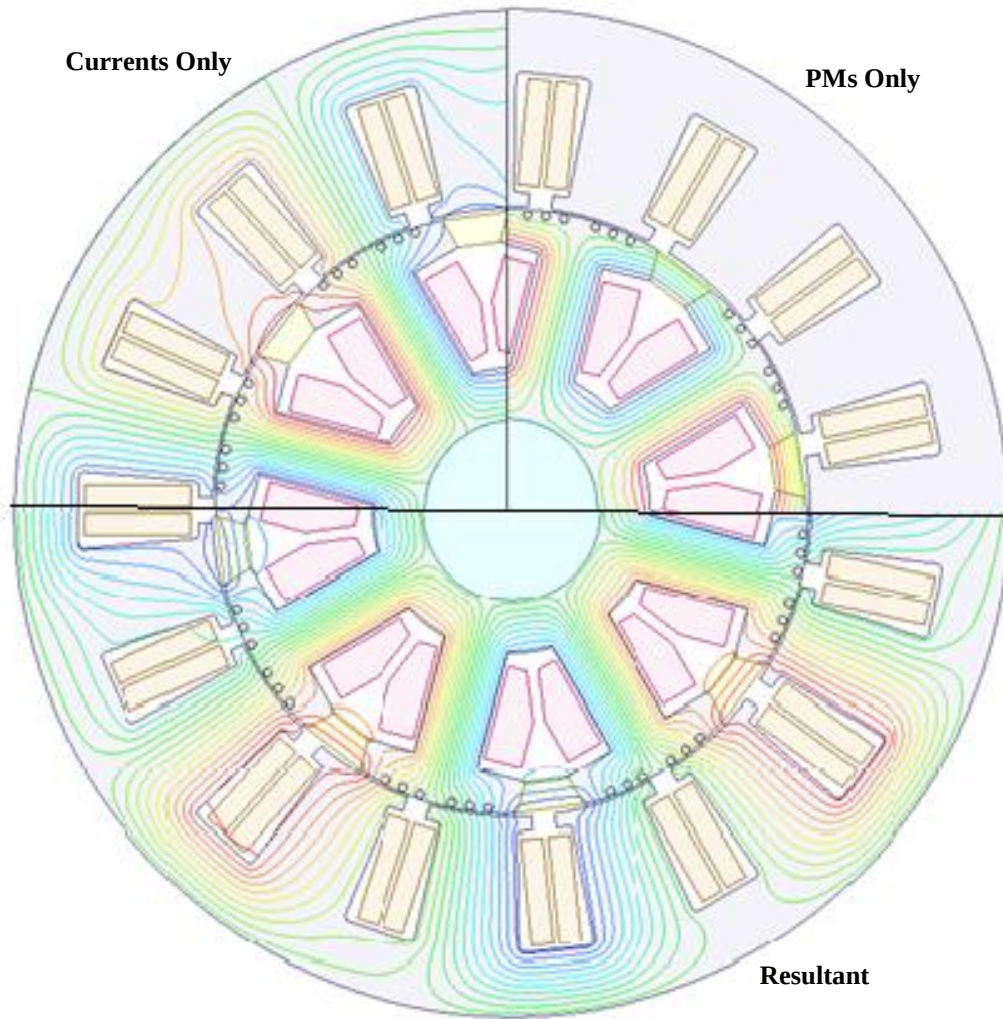


Figure 5.9 : Flux lines showing frozen permeability solution.

Via this technique, the effect of the PMs to total flux-linkage and also reason of the increasing output voltage can be figured out easily by separately visualizing the flux path of the additional PMs. In other words, the frozen permeability method has been used as a means of determining the proportion of total flux-linkage attributable to the PMs and phase current. For the given rotor position and load current an initial nonlinear solution is calculated and the resulting permeability in each element of the finite element meshes are stored. Using these permeability, after the calculation of the magnetic field of the windings given in (5.15) by setting the remanent flux of the PMs to zero firstly (currents only), and then magnetic field of the additional PMs can be calculated by setting the phase currents to zero (PMs only). The sum of the two individual components will equal the total flux-linkage. Flux plots corresponding to the separate frozen permeability solutions and resultant flux-linkage are shown in Fig. 5.9. As it clarified in Fig. 5.9, PM flux flows only in the rotor because; the

reluctance of the air-gap is considerably greater than the reluctance of the rotor core. Under that condition, the effect of the PM fluxes to the stator is very small. For the aPM-FSCW SPSG developed version of the FSCW SPSG, the frozen permeability technique with FEM is adopted. Additional to these, a simple magnetic circuit of aPM-FSWC machine is prepared and also all results are verified by FEM results.

5.2.2.3 Magnetic circuit

To be able to understand the mechanism of the increasing voltage and decreasing saturation caused by the PMs a simple approximated nonlinear magnetic circuit is designed as given in Fig. 5.10. On the other hand, only $\mathcal{R}_m$, $\mathcal{R}_g$ and $\mathcal{F}_f$ will be in the model of CSDW machine's magnetic circuit.

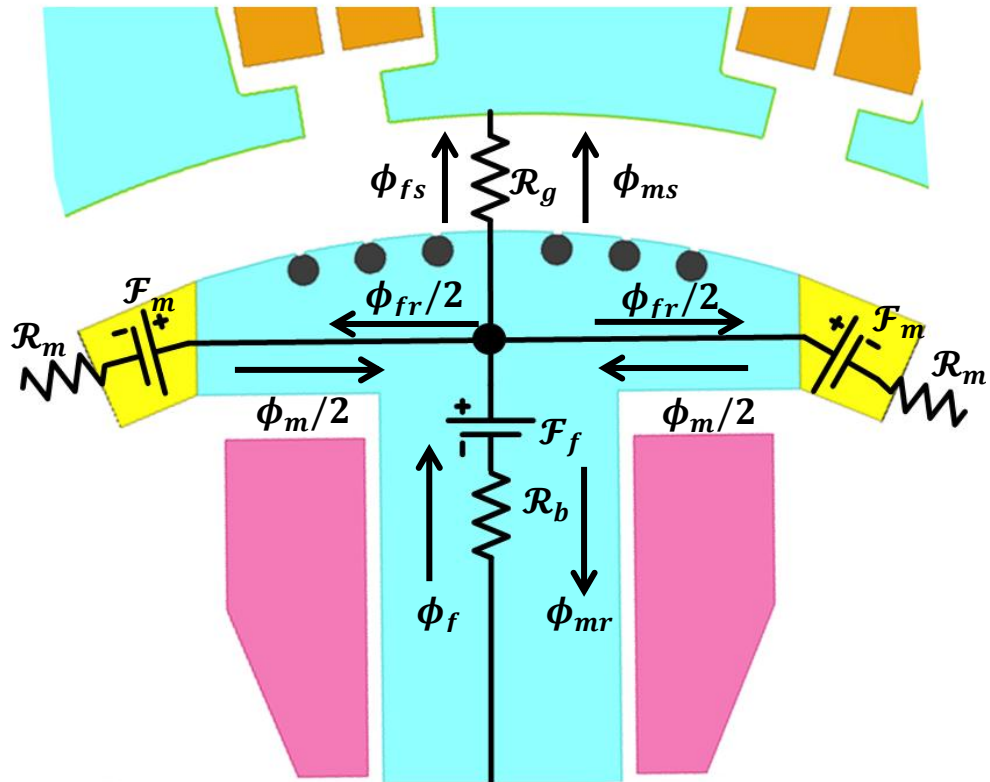


Figure 5.10 : Approximated nonlinear magnetic circuit.

Proposed circuit consists of rotor pole-body, PM, and air-gap reluctances indicated by $\mathcal{R}_b$, $\mathcal{R}_m$ and $\mathcal{R}_g$, respectively and MMFs which are belong to field winding and PM ($\mathcal{F}_f$ and $\mathcal{F}_m$). It is assumed that the reluctance of the core is a function of rotor pole-body flux considering the B-H curve of the core material. ($\mathcal{R}_b = f(\phi_b)$). Induced MMFs are given by in the terms of magnetic flux and reluctance as (5.18).

$$F_m = \phi_m \left(\frac{\mathcal{R}_m}{2} + \frac{\mathcal{R}_g \mathcal{R}_b}{\mathcal{R}_g + \mathcal{R}_b} \right) + \phi_f \mathcal{R}_g \quad (5.18)$$

$$F_f = \phi_f (\mathcal{R}_g + \mathcal{R}_b)$$

Or, if field current and magnetic field density of the PM are known, induced MMFs can be calculated as follows.

$$F_m = M \frac{l_m}{\mu_m} = H_m l_m \quad (5.19)$$

$$F_f = N_f i_f = H_b l_b$$

PM flux consists of rotor and stator components as seen in Fig. 5.9, and they can be calculated easily by the inverse ratio of rotor-body and air-gap reluctances as (5.20). The ϕ_{ms} directly contributes the armature voltage increase while the ϕ_{mr} reduces the magnetic saturation at the rotor pole-bodies. As it figured out from the Fig. 5.9, ϕ_{mr} causes the reduction of magnetic saturation by reducing the ϕ_f which can be calculated as in (5.21). The approximate total flux of the rotor pole-body can be calculated as in (5.22).

$$\phi_{ms} = \left(\frac{\mathcal{R}_b}{\mathcal{R}_g + \mathcal{R}_b} \right) \phi_m \quad (5.20)$$

$$\phi_{mr} = \left(\frac{\mathcal{R}_g}{\mathcal{R}_g + \mathcal{R}_b} \right) \phi_m$$

This indicates that the unsaturated region has been enlarged by the additional PMs. In addition, no saturation on the poles leads to higher output voltage.

$$\phi_f = A_b \frac{3\mu_0 I_f N_f}{g\pi} \sum_h \frac{1}{h} k_{so} k_{ap} Fv(r) \sin[Pw_r t \mp h\alpha + \theta] \quad (5.21)$$

$$\phi_b \approx \phi_f - \phi_{mr} \quad (5.22)$$

In different words, the permeability of the rotor pole-body increases. Reluctances can be calculated as (5.23) using the relative permeability distribution of designed machines and B-H curve of the core material. Averaged values of the each pole body, shoe and yoke may be used for simplifying the calculations.

$$\mathcal{R}_\delta = \frac{1}{g\mu_0 A_\delta}, \quad \mathcal{R}_b = \frac{l_b}{\mu_{rb}\mu_0 A_b}, \quad \mathcal{R}_m = \frac{l_m}{\mu_{rm}\mu_0 A_m} \quad (5.23)$$

The fluxes at each branch of the magnetic circuit can be obtained by solving (5.18) and (5.20) along with acceptable approximations, the increase in the armature flux $\Delta\phi_{fs}$ which causes increase in the output voltage can be derived as in (5.24).

$$\Delta\phi_{fs} \approx \phi_m \mathcal{R}_g \left(\frac{1}{\mathcal{R}_b + \mathcal{R}_g} - \frac{d\phi_b}{d\mathcal{F}_f} \right) \quad (5.24)$$

This expression implies that the effect of the PMs to the total flux depends on the differential function of ϕ_b . Then, the total magnetic flux flowing through the air-gap can be given as (5.25).

$$\phi_s = \frac{N_f}{\mathcal{R}_g} = \phi_{fs} + \phi_{ms} \quad (5.25)$$

Consequently, line-line voltage increased by ϕ_{ms} can be calculated as follows:

$$V_L \approx 7.7k_{wh}fN_{ph}\phi_s \quad (5.26)$$

5.3 Calculation of EMF, Harmonics & THD

Based on the analysis of the air-gap magnetic field waveform, taking into account coil short pitch, winding distribution, skew slot, winding connection, load effects and other factors, the EMF waveforms in the coils and the windings are analyzed to solve for the EMF distortion factors.

Harmonics have the effect of increasing equipment copper, iron and dielectric loss and thus the thermal stress. Calculation of the EMF and also output-voltage waveform of the generator depend on the various harmonic winding factors that

result from the adoption of concentrated windings. The actual harmonics of a FSCW machine has been shown in [166] that;

$$\left(\frac{n'}{p} + 1\right)\frac{\beta}{2} = K, \quad \left(\frac{n'}{p} \mp 1\right)\frac{\beta}{2m} = K_m \quad (5.27)$$

where K and K_m are integer including 0. n' , p and β are order of the harmonic with respect to a fundamental whose wave length is equal to the circumference of the rotor, number of pole pairs and denominator of the fraction that fixes the number of the q value, respectively. (a) and (b) are the criteria for the existence of the n' th harmonic in the MMF of a FSCW. When the minus sign is used in the (b) the harmonic travels with the rotation; when the plus sign is used, the harmonic travels opposite to the rotation. The actual and sub-harmonics produced by FSCW is different for different values of β and p . As it known as well, in an electrical machine that has balanced three phases; the harmonics which are multiple of three do not exist except when zero-sequence currents flow in the winding. The air-gap flux density distribution produced by field windings, neglecting the slot effect and the magnetic flux leakage and without giving sinusoidal shape to pole shoes (pole arc offset=0) between the poles, is ideally a square wave consisting of all odd harmonics as shown in Fig. 5.11. It can be expressed in Fourier series as (5.28) [116].

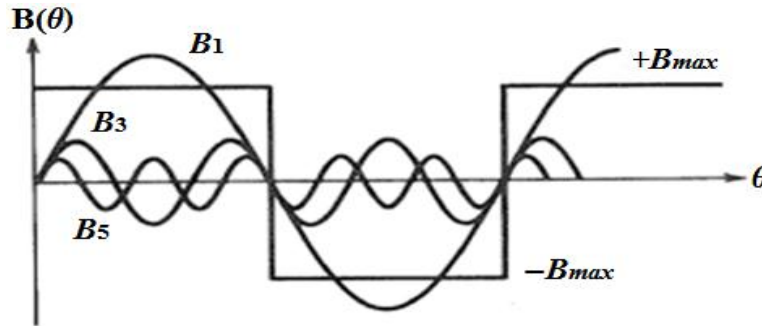


Figure 5.11 : Concentrated winding air-gap flux density distribution.

$$B(\theta) = \sum_{h=1,3,5,\dots}^{\infty} B_h = \sum_{h=1,3,5,\dots}^{\infty} \frac{4B_{max}}{\pi h} \sin(h\theta) \quad (5.28)$$

where h is the harmonic order, B_h is the h order component of the flux density, B_{max} is the maximum flux density of the square waveform. According to Faraday's law, all the odd harmonics also present in the induced back EMF of a full-pitch turn in an

electrical machine when the flux rotates, and the induced EMF (e) can be expressed by (5.29).

$$e = \frac{d\Psi}{dt} = \sum_{h=1,3,5,\dots}^{\infty} e_h \quad (5.29)$$

where Ψ is the magnetic flux, e_h is the induced EMF component by the h order flux. For an electrical machine with N_{ph} -turn coil windings per phase, the resultant phase EMF (e_{ph}) is calculated by (5.30).

$$e_{ph} = \sum_{h=1,3,5,\dots}^{\infty} N_{ph} k_{wh} \Psi_h P \sin(hP\theta) \frac{d\theta}{dt} = N_{ph} \sum_{h=1,3,5,\dots}^{\infty} e_h k_{wh} \quad (5.30)$$

where k_{wh} is winding factor of the h order harmonic can be obtained from (5.2). The most challenging aspect of calculating back EMF waveform is determining the various harmonic winding factors that results from the adoption of concentrated windings. There are several alternative methods for accomplishing this task, including some approaches that yield closed-form solutions [7, 167]. The amount of distortion an EMF is quantified by THD defined by (5.31).

$$THD\% = \frac{100}{e_1} \left(\sqrt{\sum_{h=1,3,5,\dots}^{\infty} e_h^2} \right) \quad (5.31)$$

From (5.30) and (5.31), it is know that the harmonic component of e_h is inversely proportional to the harmonic order h , so the distortion is mainly determined by the low harmonics.

5.4 Losses & Slot Ripple

Basically, losses in an electrical machine consist of five groups:

- stator and rotor winding copper losses,
- iron core losses including stator and rotor iron core,
- windage and frictional losses (mechanical losses),
- additional losses,

- stray losses,

and there are different calculation methods in literature for these losses [168-173]. Copper losses in conductors are sometimes called Joule losses or resistive losses. For a three-phase synchronous copper losses in a winding can be calculated as (5.32).

$$P_{cu} = P_{cuS} + P_{cuR} = 3I_{ph}^2 R_{AC} + I_f^2 R_R \quad (5.32)$$

where R_{AC} is the AC resistance of the phase winding, P_{cuS} and P_{cuR} are indicated the stator and rotor copper losses respectively, I_{ph} and I_f are phase and field current.

The iron losses include hysteresis (P_h), eddy-current (P_c) and excess loss (P_e) components as it given in (5.33), and they can also calculate by different methods [166, 167, 174, 175].

$$P_{FE} = P_h + P_c + P_e \quad (5.33)$$

$$P_h = k_n \frac{1}{T} B_{max}^2$$

$$P_c = k_c \frac{1}{2\pi^2} \frac{1}{T} \int_0^T \left| \frac{dB_{max}}{dt} \right|^2 dt \quad (5.34)$$

$$P_e = k_e \frac{1}{8.76} \frac{1}{T} \int_0^T \left| \frac{dB_{max}}{dt} \right|^{1.5} dt$$

Furthermore, iron losses can be calculated using the FEM with time stepping as in (5.34), which means that the actual flux density variation over one electrical period is calculated. Hysteresis and excessive loss coefficients k_n and k_e respectively are obtained by curve fitting of the lamination manufacture's loss data recorded for different frequencies. The classical eddy-current loss coefficient is calculated by;

$$k_c = \sigma \frac{(\pi d)^2}{6\rho} \quad (5.35)$$

where σ is the conductivity and d is the thickness of one lamination sheet and ρ is the mass density of the magnetic steel. The eddy current and excessive loss is caused by the rate of cycling of the flux through the atomic structure and hence the equations within the time domain have derivatives. The hysteresis loss is highly

dependent upon the magnitude of the peak flux and thus the saturation of the material. Friction loss, given in (5.36), known as brush friction loss is mechanical loss that occurs as a result of the axis of the rotating machine turning.

$$P_F = K_B \frac{2\pi n}{60} \quad (5.36)$$

K_B is a parameter that is determined using the mass applied to the bearings, the diameter of the axis, and the peripheral velocity of the axis, and n is the speed of the rotating machine. For calculation of the wind losses (P_W) the approximation shown in (5.37) is used, because accurate calculations of wind loss are in general very difficult.

$$P_W \approx K_W \left(\frac{2\pi n}{60} \right)^2 \quad (5.37)$$

K_W is a parameter that is determined using the external shape and length of the rotor, and the peripheral velocity of its surface. The other loss in an electrical machine is stray loss, which occurs in the windings and PMs due to eddy current losses. This loss includes iron loss that occurs as a result of a conductor with leak flux, eddy current loss due to adjacent metal parts, and flux density distortions in the gap. The stray loss (P_s) can be calculated as in (5.38), where P_{in} is generated power and P_{out} is the output of the machine.

$$P_s \approx \frac{5P_{in}^2}{P_{out}} 10^{-3} \quad (5.38)$$

Additional losses are very difficult to calculate and measure. So, to be able to approximately calculate these losses in an easy way, the additional losses are assumed to be 0.5-1% and mechanical losses are assumed 1-3% of the output power in synchronous machine when the efficiency of the machine is calculated indirectly from the loss measurements [170]. Additional losses (P_{ad}) are proportional to the square of the load current and to the power of 1.5 of the frequency, that is;

$$P_{ad} = I_L^2 f^{1.5} \quad (5.39)$$

If additional losses are measured or known for one pair of the current and frequency, they can be determined for another pair of current and frequency using (27). The slot

ripples are the consequence of the air-gap permeance fluctuation caused by stator slotting. The stator slot openings produce permeance variations in the air-gap, which are reflected as ripples in the air-gap flux density waves. Since slot ripples caused by the stator harmonic currents is time harmonic, it produces eddy current and thus iron loss if a metallic sleeve exists on the rotor surface. So, the iron loss can be calculated approximately by (5.40) [176].

$$P_{FE} \approx \frac{\pi}{1800\rho} (B_0 n)^2 D^3 l d \quad (5.40)$$

Where n is the speed in rpm, B_0 is the amplitude of the slot ripple, D , d and ρ are the average diameter, thickness and the resistivity of the sleeve respectively. As it seen in (5.40), iron loss is directly proportional to square of the amplitude of slot ripple. The amplitude of the slot ripple is approximately given by (5.41).

$$B_0 \approx \frac{1 + u^2 - 2u}{2(1 + u^2)} k_c B_g \quad (5.41)$$

where u and k_c which is the Carter's coefficient is given by (5.42).

$$u = \frac{b_0}{2g} + \sqrt{1 + \left(\frac{b_0}{2g}\right)^2} \quad (5.42)$$

$$k_{ca} = \left\{ 1 - \frac{g}{\tau} \left[\frac{(b_0 g^{-1})^2}{5 + b_0 g^{-1}} \right] \right\}^{-1}$$

where B_g is the average flux density over the air-gap. According to above equations, slot opening width can be decreased or/and the air-gap length can be increased to be able to reduce the slot ripple. The model chosen for this analysis has very deep rectilinear and small number of slots, making it an attractive choice for FSCW configurations. Furthermore, slotting reduces the total magnetic flux linkage per pole as a result of Carter's coefficient and it affects the distribution of the flux in the air-gap [28]. After the calculation of the losses and the input power, the efficiency of the electrical machine can be given as (5.43).

$$\eta = 1 - \left(\frac{P_{cu} + P_{FE} + P_{FW} + P_s + P_{ad}}{P_{in}} \right) \quad (5.43)$$

6. DESIGN & ANALYSIS

After the first step, which is very important for designing a SPSM to achieve lighter, cheaper and high-efficiency SPSGs with more simple structure and allows increasing the permeability of the pole body iron cores using FSCW is to choose the optimum q , the accurate analytical approach should be chosen for proper analysis and its results.

Next, designed FSCW is developed by adding PMs between the rotor pole-shoes to be able to prevent the saturation of the pole body. Detailed technical data is given by comparison. Obtained data are analyzed by using FEM to prove the accuracy of implementation of the FSCW method on large SPSGs and also its development. Analysis results including magnetic density, flux lines, relative permeability and performance curves are given in section 6.2 and estimated active material cost analysis is given in section 6.3.

To test and compare the all mechanical and characteristic properties, a double-layer 15 slots-8 poles (15Q8P), 2.4MVA, 6.6kV/50Hz FSCW SPSG was designed and compared with double-layer 69 slots-8 pole (69Q8P), 2.4MVA, 6.6kV/50Hz conventional SPSG. The requirements were modified to require infinite bus operation as a generator which is synchronized with network (50Hz, 6.6kV constant voltage). After this process, FSCW machine has been developed by additional PMs between the pole shoes in order to decrease the saturation point of the pole bodies.

6.1 Design Parameters

Table 6.1 summarizes the requirements for the designed machines. The key machine dimensions and used materials for cores are given in Table 6.2. Only the stators of the FSCW SPSG design and aPM-FSCW SPSG design were skewed with 0.7 skew width values to be able to obtain more stable output parameters. The same iron cores "M36_29G_SF0.774 ($k_n=273.56$, $k_c=0.61$, $k_e=0$)" for the stator and "M36_29G_SF1.039 ($k_n=203.67$, $k_c=0.45$, $k_e=0$)" for the rotor are used to compare the magnetic flux densities to be able to figure out the saturations in the cores. In

addition, C-5 insulation class is chosen for iron core isolation. Electrical steels for iron cores and their insulation classes are given respectively in Appendix E and F which are meet the standards of IEC60034 [177-179].

Table 6.1: General data.

Rated Apparent Power (MVA)	2.4
Rated Power Factor	0.8 (Ind.)
Rated Voltage (kV)	6.6 (Inf. Bus)
Winding Connection	Wye
Number of Poles	8
Frequency (Hz)	50
Rated Speed (rpm)	750
Friction and Windage Loss at Reference Speed (kW)	9.05
Exciter Efficiency (%)	95

Table 6.2: Stator data.

Stator Feature	CSDW	FSCW	aPM-FSCW
Number of Stator Slots	69	15	15
Outer Diameter of Stator (mm)	1090	1120	1065
Inner Diameter of Stator (mm)	748	698.5	643
Top Tooth Width (mm)	17.0537	101.75	82.11
Bottom Tooth Width (mm)	26.0656	137.93	111.47
Length of Stator Core (mm)	760	600	560
Number of Sectors per Lamination		1	
Stacking Factor of Stator Core		0.9	
Type of Steel		M36_29G	

Table 6.3: Stator slot data.

	Part (mm)	CSDW	FSCW	aPM-FSCW
	Hs0	1	8	13
	Hs1	3	2	2
	Hs2	95	135	120
	Bs0	17	25	25
	Bs1	17	48.6	59
	Bs2	17	69	80
	Rs	0	6	6

Stator slot shape and its key dimensions are given in Table 6.3. In the FSCW design the slot depth is 142,105% larger than CSDW design as it seen from “Hs2” indicating the depth of the stator slot and the average width of the slot “(Bs1+Bs2)/2”

345.882% larger than CSDW machine. On the other hand average slot width of the aPM-FSCW generator is the largest as it can be also figured out from the net slot area indicated in Table 6.4. The reason why the aPM-FSCW machine has the largest slot area is that it has the shortest active machine length. So, more ampere-turns is required to be able to meet the same output power with other machines.

Table 6.4: Stator winding data.

Winding Feature	CSDW	FSCW	aPM-FSCW
Number of Conductors per Slot	16	110	116
Net Slot Area (mm²)	1683	8170.12	8615.49
Number of Wires per Conductor	1		1
Wire Width (mm)	8.2		-
Wire Thickness (mm)	5		-
Wire Diameter (mm)	-		7.348
Wire Wrap Thickness (mm)	0.11		0.26
Wire Direction in Slot	Horizontal		Horizontal
Wedge Thickness (mm)	3		2.1
Layer Insulation (mm)	2		2
Slot Fill Factor (%)	62.67		77.93
Fundamental Stator Winding Factor	0.9135		0.711

Stator-winding data designed for both machine is given in Table 6.4. To test and compare the all mechanical and characteristic properties, no. of slots per pole per phase (q) value is chosen as 0.625 for both designs. Addition to this, the optimal q value is chosen for high efficiency and smooth sinusoidal wave form of the induced voltages which leads to low THD, low cogging torque in two teeth and more stable output values by experimentally. To obtain the same output voltage, aPM-FSCW's number of conductors per slot has been increased in order to tolerate the shrinking size of the machine via optimization. Slot fill factor of concentrated winding design increased up to 78% with pre-pressed windings [119]. For 15 slot, 8 poles (15Q8P) machines the standard winding factor has been determined as 0.621 as given in Table 1. After the experimental combination of the pitch and distribution factors, this value has been increased up to 0.711 (14.485% increase). On the other hand the winding factor of CSDW machine is 128,661% higher than FSCW and aPM-FSCW machine. General rotor dimensions and parameters are given in Table 6.5. Pole dimensions of the aPM-FSCW are lower because of the assist effect of the additional PMs between the pole-shoes. Although the average relative permeability of the aPM-FSCW design is 184% higher than FSCW design as it shown in Fig.6.10, the pole-

body width of the aPM-FSCW is 33.33% lower. In addition, aPM-FSCW requires lower exciter current because of additional PMs' fixed excitation.

Table 6.5: Rotor data.

Part	CSDW	FSCW	aPM-FSCW
Minimum Air Gap (mm)	3	3.25	2.5
Inner Diameter (mm)	220	200	190
Length of Rotor (mm)	760	600	560
Stacking Factor of Core		0.96	
Type of Steel		M36_29G	
Polar Arc Offset (mm)	10	62	30
Mechanical Pole Embrace	0.73	0.754	0.715
Pole-Shoe Width (mm)	210	200	176
Pole-Shoe Height (mm)	48	42	40
Pole-Body Width (mm)	110	105	70
Pole-Body Height (mm)	130		125

The detailed parameters of field-winding data of the designed machines are given in Table 6.6. As it figured out from the table, all field winding parameters are almost same expect number of turns per pole and wire diameters. To provide approximately the same output quantities aPM-FSCW design is required more number of turns or larger PMs between the pole-shoes because, the outer diameter of aPM-FSCW is 5% and length is 6.7% lower than FSCW. Taking account the PM prices, optimum PM dimensions has been chosen.

Table 6.6: Field winding data.

Winding Feature	CSDW	FSCW and aPM-FSCW
Number of Parallel Branches		1
Winding Type		Edgewise
Width of Wire (mm)	39	31.5
Thickness of Wire (mm)	1.06	1.18
Number of Turns per Pole	76	70/73*
Wire Wrap Thickness (mm)		0.3
Under-Pole-Shoe Insulation (mm)		3
Pole-Body-Side Insulation (mm)		3
Clearance between Windings (mm)		6
Inside Corner Radius (mm)	76	86

*73 for the aPM-FSCW generator.

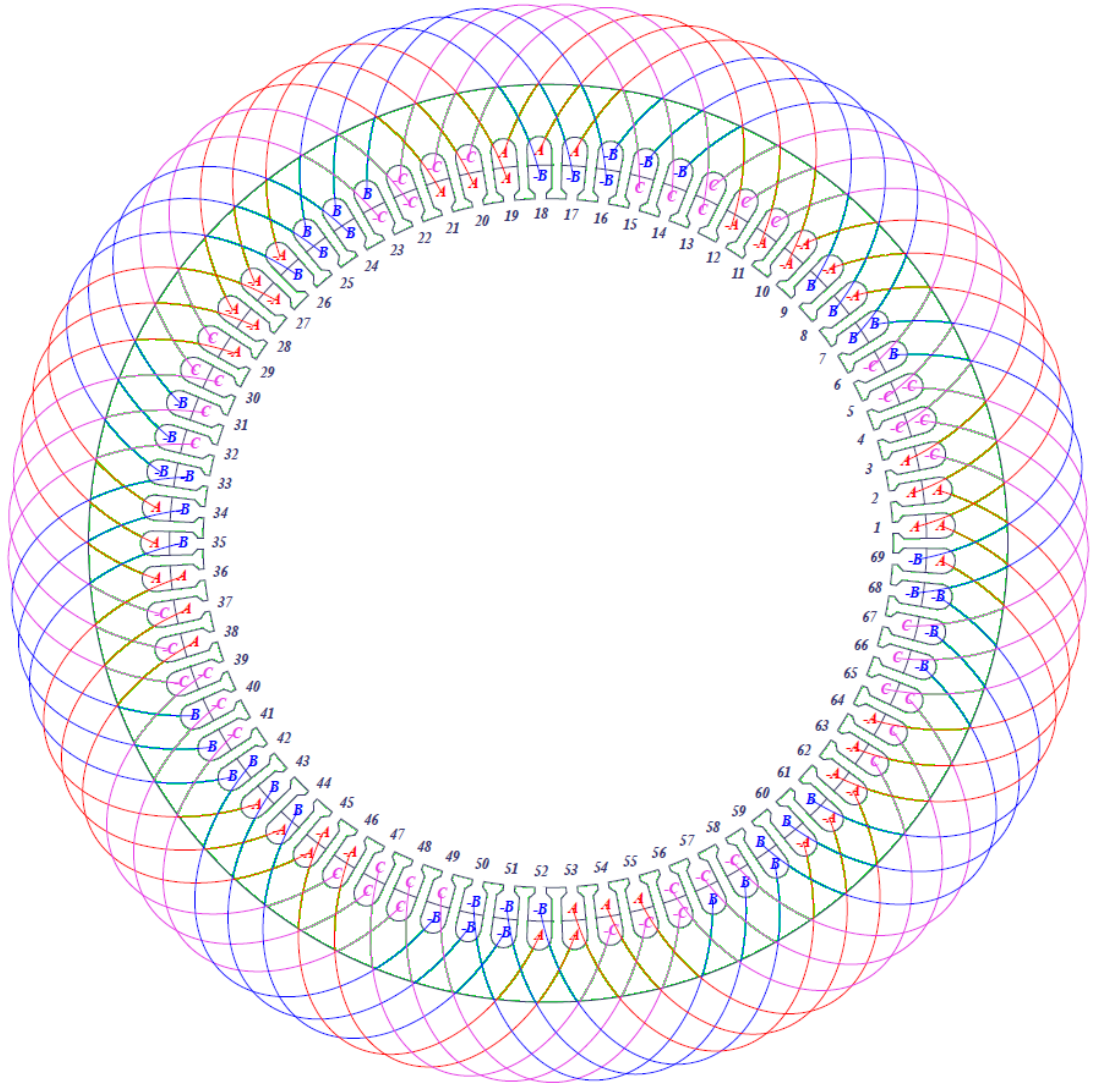


Figure 6.1: Stator winding topology of designed 69Q8P (CSDW) SPSG.

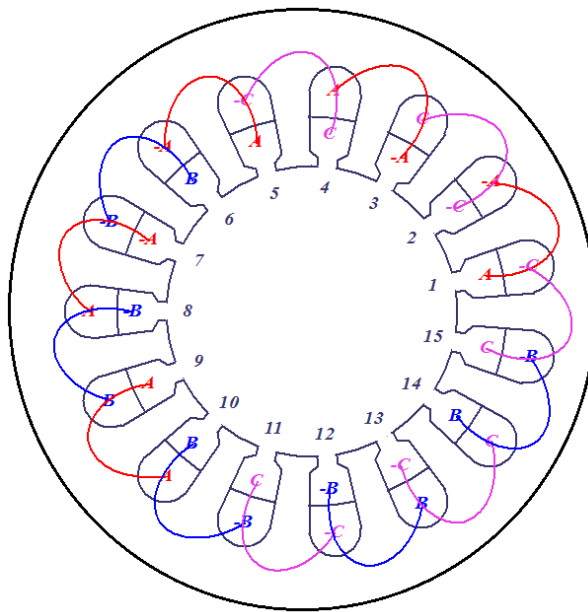


Figure 6.2: Stator winding topology of designed 15Q8P (FSCW) SPSG.

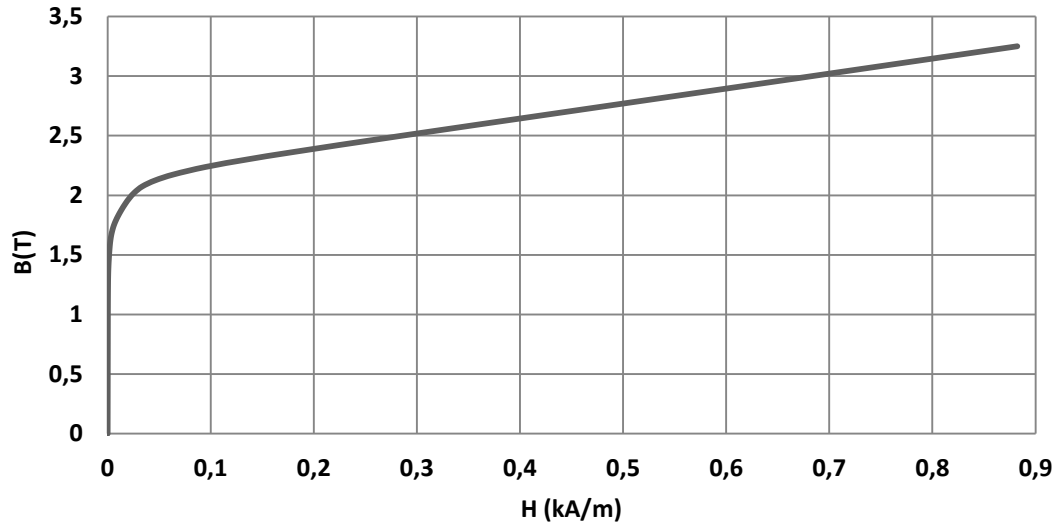


Figure 6.3: B-H curve of the core material (M36_29G).

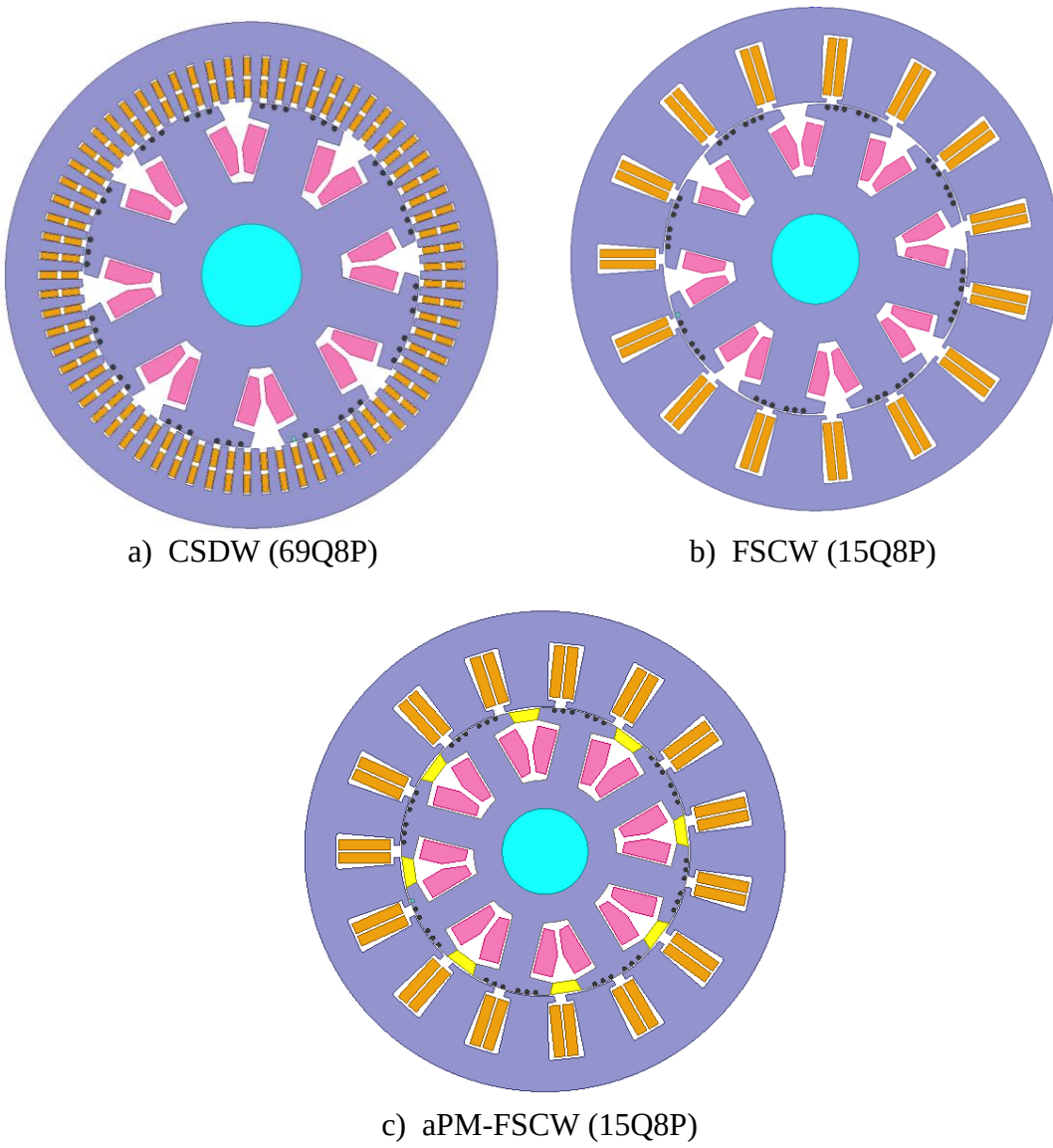


Figure 6.4: 2D view of the designed SPSGs.

After required calculations whose results are summarized in Table 6.6, stator winding topology diagrams of the both designed generators are shown in Fig. 6.1 and 6.2 to be able to indicate the structural differences of the winding configurations. CSDW generator's end windings are longer because of its longer coil pitch and also it has a more complex winding structure as it seen clearly from the figures.

According to these required parameters, the 2D transient magnetic field analysis was performed using the FEA software. M36_29G (mass density 7700 kg/m^3) material whose B-H curve given in Fig. 6.3 has been used for iron cores of both stator and rotor, NdFeB35 (max. operation temperature 300°C , remanent flux density 1.23 T , coercivity 900 kA/m , relative permeability 1.09 , mass density 7400 kg/m^3) rare earth PM material is used for additional PMs and copper (bulk conductivity 58 Ms/m , mass density 8933 kg/m^3) has been used for both field and armature windings. Cross-sectional views of the designed machines given in Fig. 6.4, after inputting the required parameters to FEA program. General properties of used PM and copper materials used in the designs are given respectively in Appendix G and H which are meet the standards of IEC60034 [179-181].

6.2 Analysis Results & Discussions

Magnetic field distribution can be found analytically for very simple geometries. In most cases, the magnetic field distribution can be obtained using some numerical methods such as FEM, Finite Difference Method, and Boundary Element Method. By using FEM, it is possible to make the accurate field calculations in the electrical machines. FEM produces the most accurate results if the geometric discretization is fine enough. FEM allows accurate determination of machine parameters through magnetic field solutions as it takes into account the actual distribution of the winding, details of geometry, and the non-linearity of the magnetic materials of an electrical machine. The machine parameters and the EMF are very important considerations for both analysis and design of electrical machines. In this study, magnetic examination of the designed brushless permanent magnet DC motors according to iron sheet package structure was performed with Maxwell 2D program. From this electromagnetic analysis, actual potential magnetic flux intensity of the motor was obtained. The simulation was completed following steps;

1. Selection of the analysis type (magnetostatic, transient, eddy current and electric),
2. Creation of the geometric model,
3. Assignment of the materials to objects in the structure,
4. Determination of the boundary conditions and mesh operation,
5. Definition of the desired sources (electromagnetic excitations) and boundary conditions for the model,
6. Compute other quantities of interest during the solution process. Quantities include forces, torques, matrices, or flux linkage,
7. Computation of the desired field solution and any other requested parameters (force, torque, and so forth),
8. Determination of the analysis setup (analysis and step time),
9. Running the analysis,
10. View the results.

All designed machines have been designed in order to meet the same generator operating output performance requirements, including 2.4 MVA at 750 rpm synchronous speed and 6.6 kV/50 Hz. After required calculations, the weights of the machined have been obtained as Table 6.7.

Table 6.7: Active material weights.

Part (kg)	CSDW	FSCW	aPM-FSCW
Armature Copper	509.565	600.55	601.496
Field Copper	424.45	283.422	267.777
Damper Bar Material	34.7845	28.1589	17.891
Damper Ring Material	146.122	125.482	91.58
Armature Core Steel	1665.45	1560.35	1292.89
Rotor Core Steel	1152.95	781.656	532.437
PM Material	-	-	49.085
Total Net Weight	3933.32	3379.62	2853.156

The aPM-FSCW machine achieves a significant reduction in the total weight compared to FSCW and CSDW machine. The aPM-FSCW machine achieves a significant reduction up to 526.5 kg (15.58%) and 1080 kg (27.46%) compared to CSDW machine in the total weight. In the aPM-FSCW and FSCW generators to be

able to induce enough voltage in the stator windings more copper were used because of the significant value of leakage reactance and also leakage fluxes in the stator, air-gap and the rotor.

Actually, concentrated windings whose coil pitches are one have the significant reduction in the length of the end turns. As a result of thus, their total length is shorter. Using this feature of FSCW machines, saturation of iron core of the machine can be prevented without reducing the length of the machine. In addition, the total length of the machine can be reduced more due to additional PMs preventing the saturation of the bodies. In this study, to be able to achieve the optimal weight the lengths of the FSCW machines are reduced so as to prevent the saturation of the rotor pole-body cores. As it figured out from Table 6.7, rotor of aPM-FSCW machine consists of lower copper (5.52%) and core material (31.88%) according to FSCW machine because, additional PMs provide the remaining excitation. In addition, aPM-FSCW machine requires 12.213% lower copper in total and 35.236% lower iron core in total. The PMs of the aPM-FSCW machine are 1.72 percent of the total weight.

Table 6.8: Waveform Factors.

THDs (%)	CSDW	FSCW	aPM-FSCW
Air-Gap Flux THD at No-Load	20.61	6.713	13.07
Phase-Voltage THD at No-Load	5.21	0.22	0.626
Line-Voltage THD at No-Load	0.31	0.03	0.022
Phase-Voltage THD at Full-Load	36.5	10.98	13.78
Line-Voltage THD at Full-Load	0.787	0.4	1.68

Waveform factors of the designed machines are given in Table 6.8. As a result of adding PMs between the pole shoes, line voltage THD of the aPM-FSCW design has increased according to FSCW and CSDW machine. On the other hand, although the stators of the all machines are skewed, FSCW has lower up to 48.63% THD value according to CSDW machine. In addition, harmonic order of the designed machines has been given in Fig. 6.5. The 3rd harmonic of the aPM-FSCW's induced voltage is higher. Furthermore, as it seen in Fig. 6.5, designed machines have not any harmonics after 3rd. But, it is considered that the harmonics which are three and multiply of the three are neglected in the three-phase balanced systems. As a natural result of flux weakening operation, value of the induced voltage of the FSCW is lower due to its higher leakage fluxes and also lower winding factor as it given in (5.30).

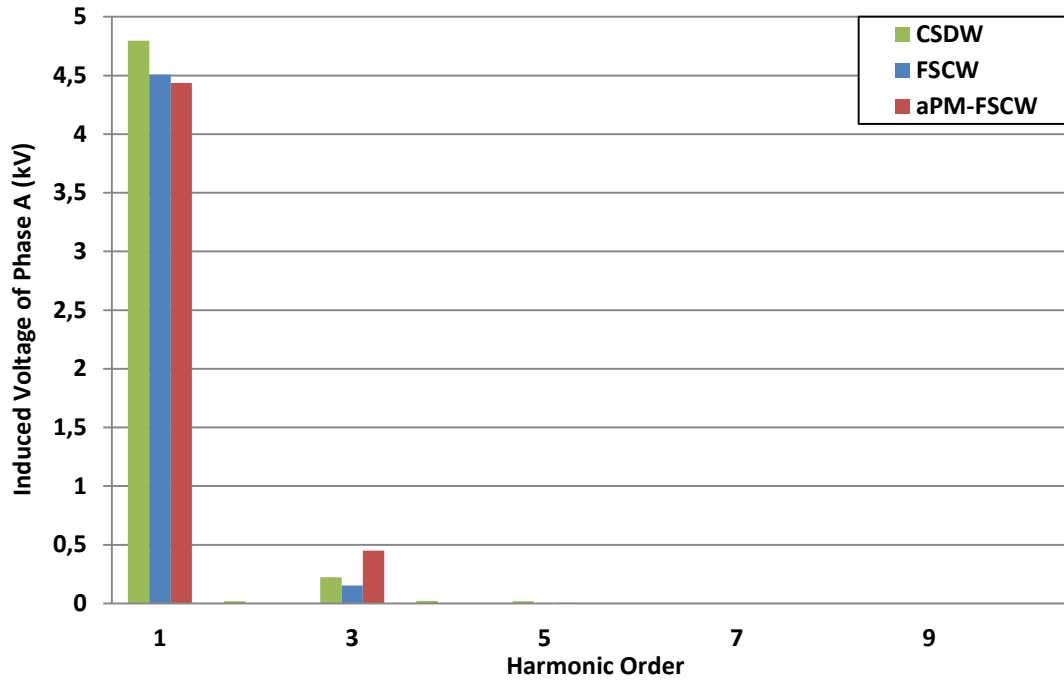


Figure 6.5: Harmonic order of the Phase A induced voltage.

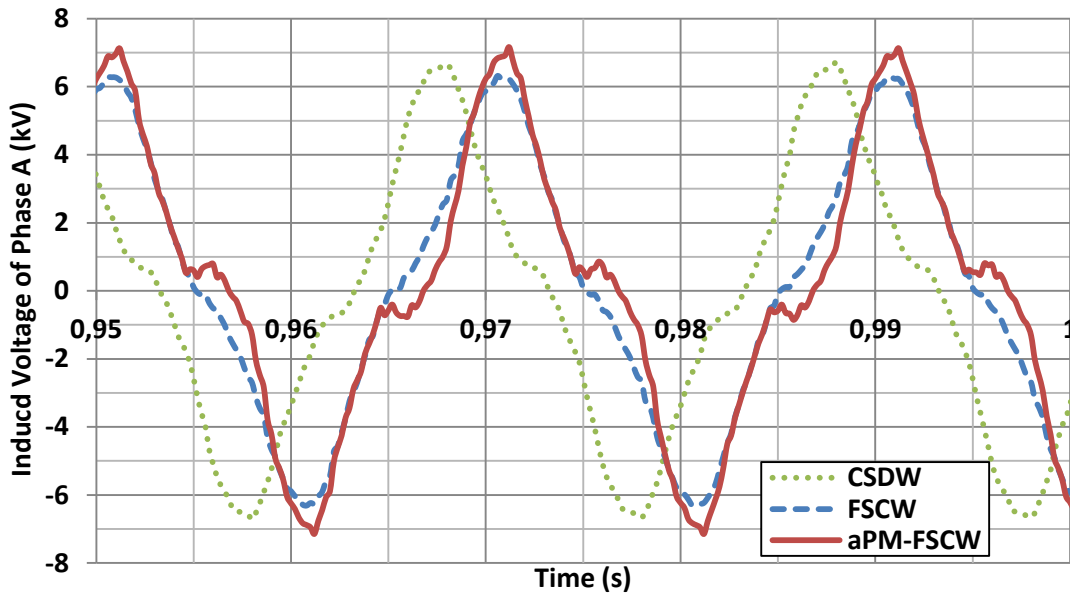


Figure 6.6: Induced voltage on the Phase A stator windings.

Waveform of the induced voltage of the aPM-FSCW machine is not smooth as FSCW or CSDW machine because of the additional PMs as it seen in Fig. 6.6. Additional PMs between the rotor pole-shoe cause extra flux leakage between the stator teeth as it seen in Fig 6.12. And this disrupts the waveform of the induced voltage in the armature windings. Besides, the waveform of the output voltage given in (5.26) will be sinusoidal due to the infinite bus connection of the machine. As it

seen in Fig. 6.6, the shape of the induced voltages is sinusoidal and includes low harmonic orders.

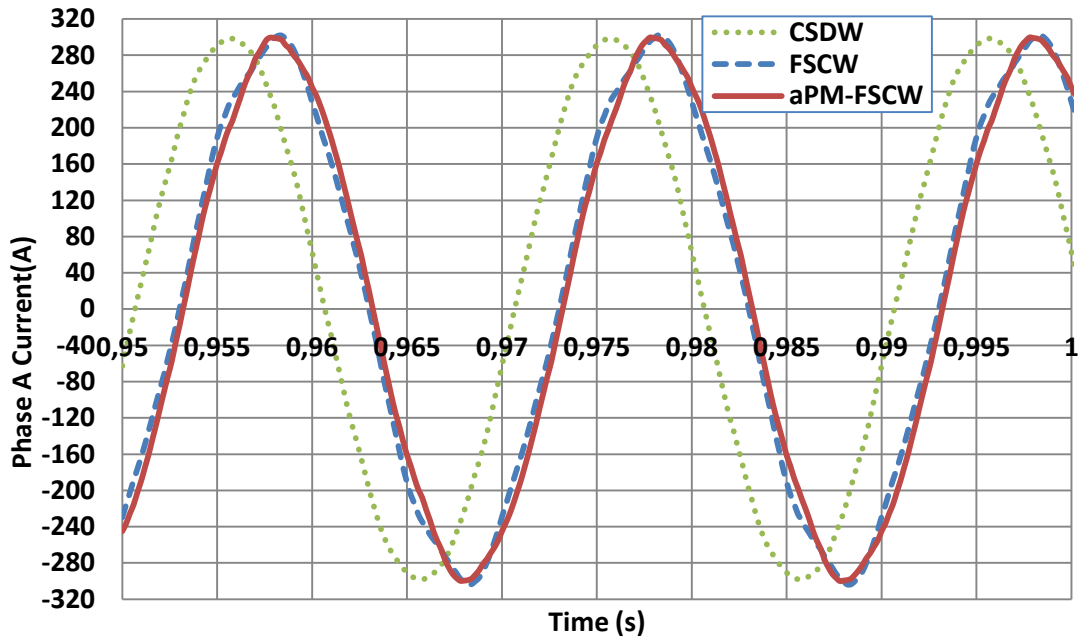


Figure 6.7: Current of Phase A at Full-Load.

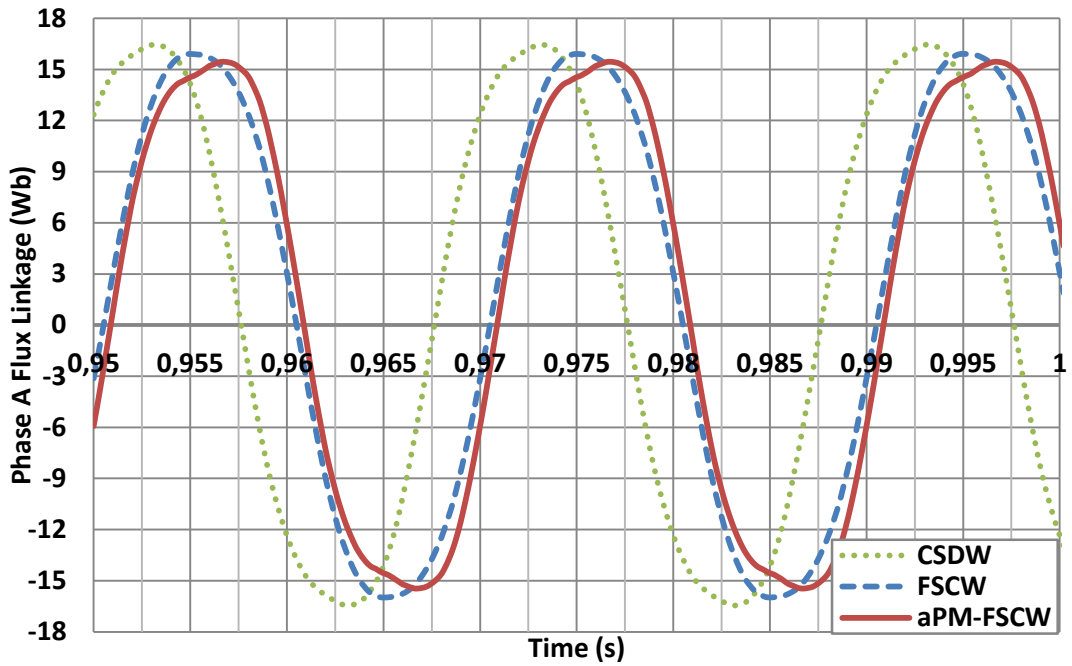


Figure 6.8: Flux linkages of Phase A under full-load condition.

Although aPM-FSCW machine has more flux leakage and shorter active length, the induced voltage on aPM-FSCW machine's stator winding is higher than FSCW machine as a result of additional PMs. The induced voltage (peak) which includes phase flux linkage, air-gap flux density and rotor position, the wave form of induced

voltage resembles its component's wave form. Fig. 6.7 and 6.8, respectively. When the designed generators are connected to the infinite bus network their current wave form will have been as in Fig. 6.7 with almost same (0.8) power factor.

Unsaturated steady state parameters of the designed machines are given in Table 6.9. Although armature copper mass of the FSCW generator heavier (17.855%) than CSDW machine, the armature resistances are almost same as seen in Table 9. Thus, the armature current density of the FSCW generator is lower. As a result of FSCW technique armature leakage reactance of the FSCW generator is significantly higher (almost 500%) than CSDW generator. Although the values of the armature resistances are almost same, the value of the leakage reactance of the aPM-FSCW is higher because of the thinner bore body of the aPM-FSCW machine.

Table 6.9: Unsaturated Steady State Parameters.

Parameters (Ω)	CSDW	FSCW	aPM-FSCW
Armature Resistance	0.29	0.3	0.3
Armature Leakage Reactance	4.57	27.38	30.66
D-Axis Reactive Reactance	75.65	78.9	96.88
Q-Axis Reactive Reactance	43.6	40.85	48.85
Field Winding Resistance	0.69	0.57	0.54

Magnetic flux densities of the designed machines at full-load generator operation given in Table 6.10 and Fig. 6.9. In addition to this, full body magnetic flux densities of designed machines at full load generator operation are given in Appendix A.

Table 6.10: Average Full-Load Magnetic Data.

Flux Densities (T)	CSDW	FSCW	aPM-FSCW
Stator-Teeth	1.78	1.14	1.33
Stator-Yoke	0.88	1.31	0.93
Pole-Shoe	1.48	1.64	1.52
Pole-Body	1.7	1.31	0.95
Rotor-Yoke	0.98	0.95	0.61
Air-Gap	0.63	0.84	0.98

In table 6.10, it is verified that the additional PMs induced more flux densities on the stator teeth which enables more induced voltage on the stator windings although the aPM-FSCW generator has the lowest dimensions. As it figured out from the average flux densities of the machine parts, although the length of the aPM-FSCW generator is 6.66%, the outer diameter is 4.91% and the pole body width is 12% shorter than

FSCW generator, it has 27.5% lower magnetic flux densities on its pole body. That's mean; aPM-FSCW generator can be operated with more load without going to saturation. Furthermore, although the dimensions (especially pole body) of the aPM-FSCW machine are lower than CSDW, its average magnetic density is lower up to 44.23%.

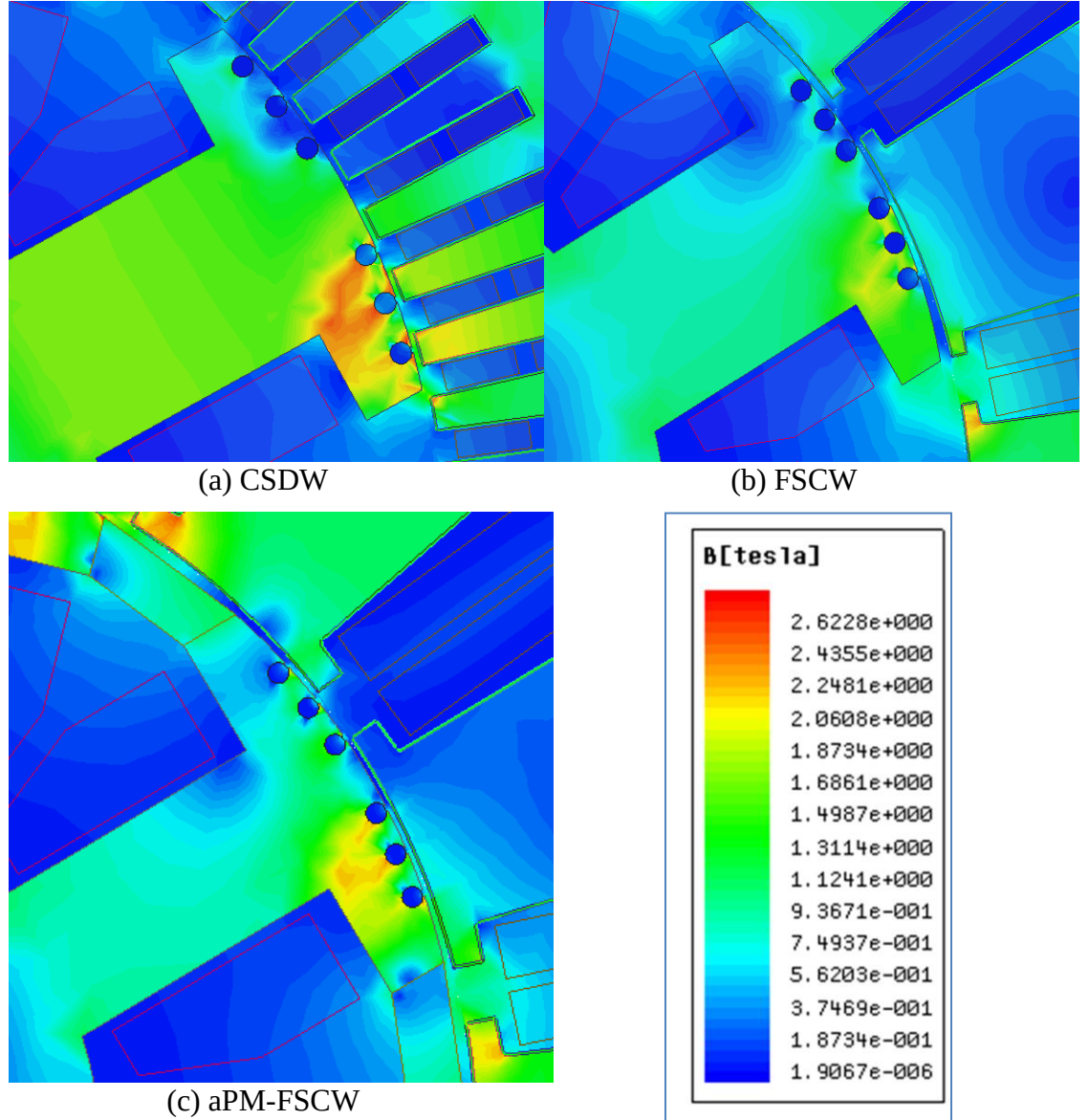


Figure 6.9: Magnetic Flux density distribution of the designed machines.

In addition, used iron core material in all designs goes to saturation after approximately 2.1T as it figured out the B-H curve of the iron core material given Fig. 6.3. Calculated average relative permeability of the aPM-FSCW generator's pole body iron core is the highest as it seen in Fig. 6.10. That's mean; although aPM-FSCW generator's pole body width is 12% narrow and height is 4.76% shorter, its average pole body permeability is 164.3% higher as a result of additional PMs.

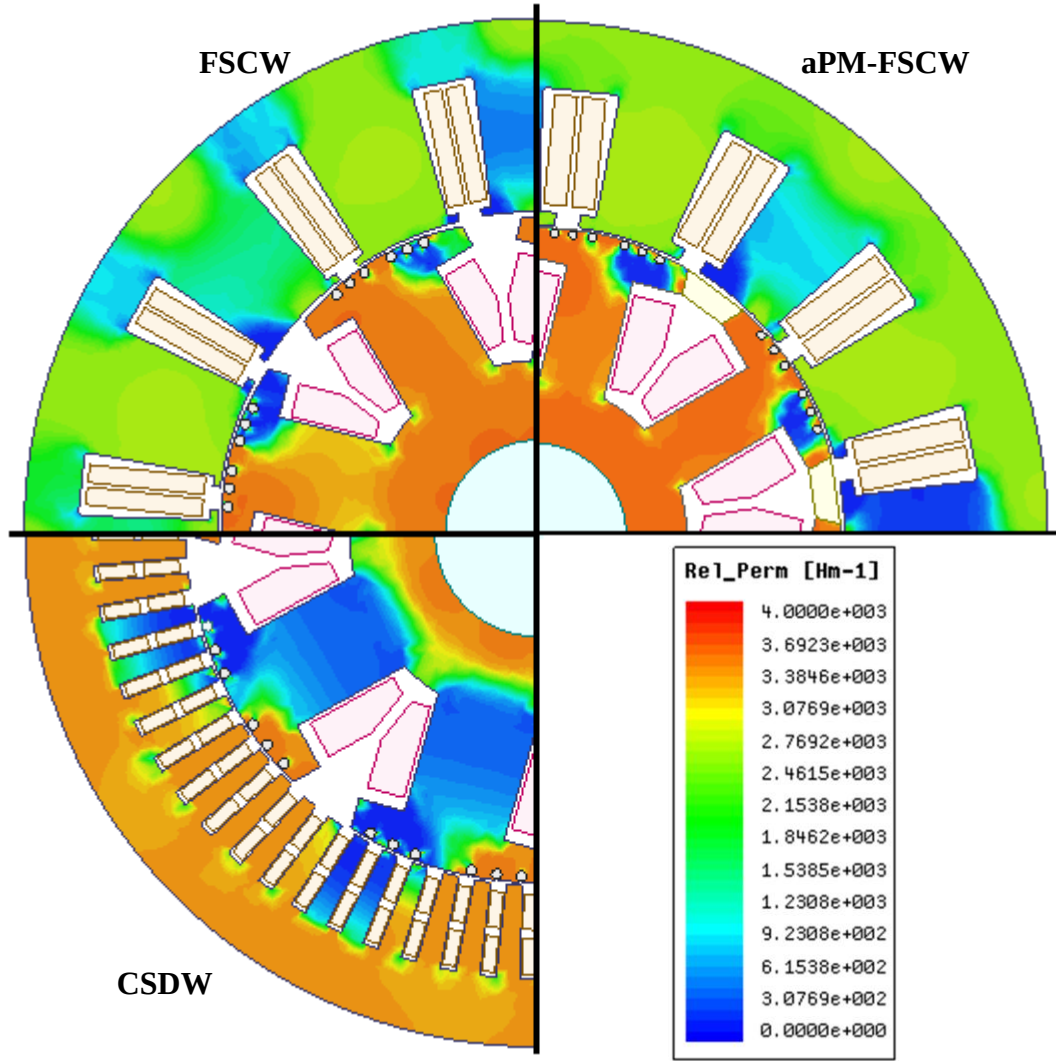


Figure 6.10: Relative permeabilities of designed machines using nonlinear magnetic core.

As a result of Fig. 6.10 and detailed full body relative permeability schemas of all designed machines given in Appendix B, it is validated that FSCW technique provide preventing the saturation of pole bodies and also this significant saturation decrease may be developed by additional PMs between the adjacent pole shoes.

To be able to figure out the performance of the aPM-FSCW after development procedure, the no-load saturation curves obtained by the FEM is given in Fig. 6.11.

From Fig. 6.11, no saturation occurs on all machines until open-circuit field current reaches up to 40A. While the terminal voltage reaches up to 4 kV FSCW and aPM-FSCW machine goes to magnetic saturation. CSDW's induced voltage at 40A is approximately 4.5kV. It is 0.5kV higher than the others because of its higher armature reactance, it requires more induced voltage. In addition to this, induced voltage of the FSCW and aPM-FSCW generators are lower than CSDW generator at

the no-load condition due to their lower winding factor, armature reaction and also lower dimensions.

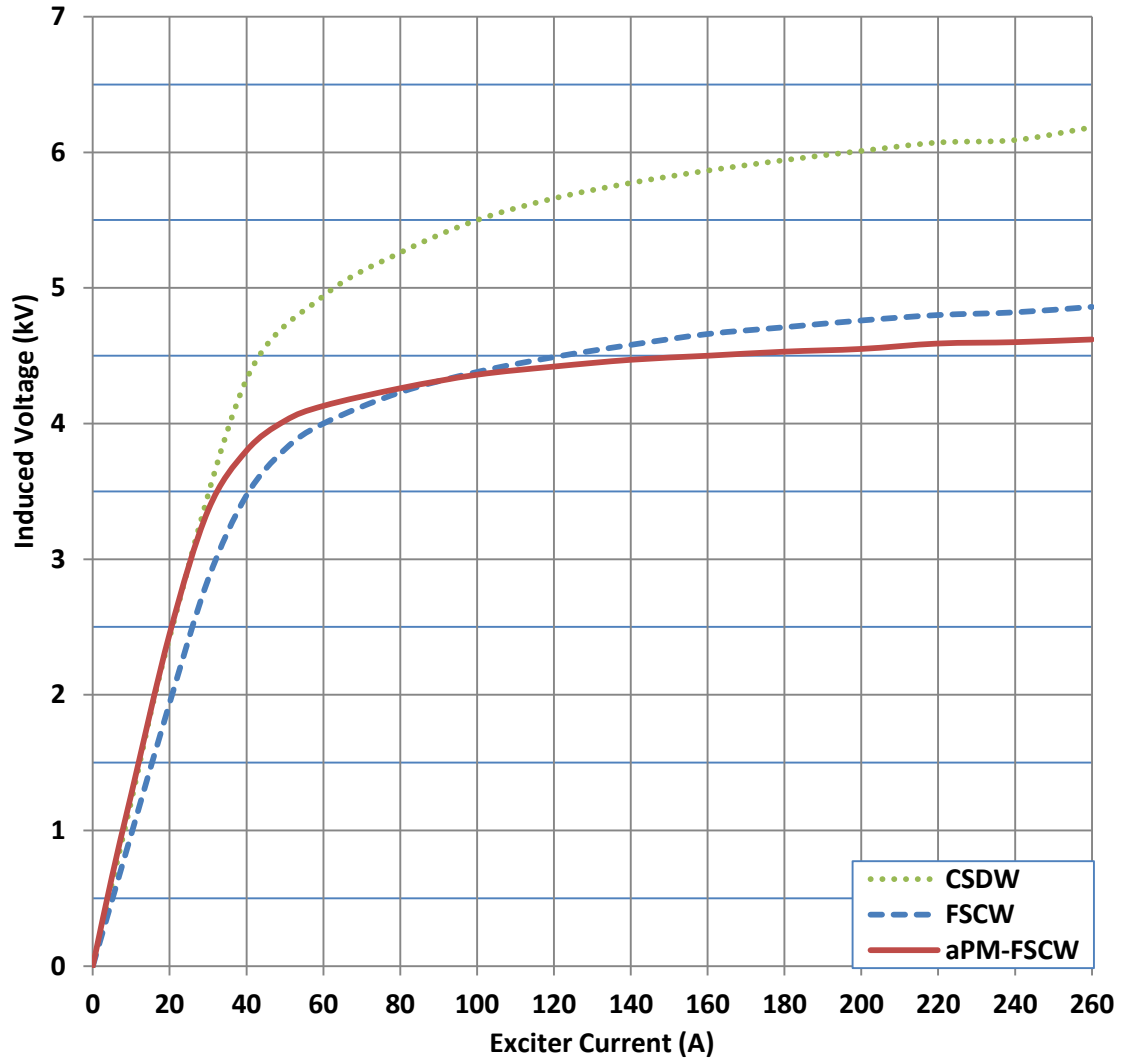


Figure 6.11: No-load (Open-circuit) saturation curves.

To be able to figure out the accurate distribution, flux leakages and the line forms, the magnetic flux line distribution of the designed machines are shown in Fig. 6.12. After the flux weakening operation, the flux leakages of the FSCW and aPM-FSCW machines are higher as expected.

Air-gap flux density which is very important in the terms of the harmonics of the induced voltage in the stator windings is given in Fig. 6.13. In addition, the air gap flux has a harmonic content that is a function of the machine saturation. As it figured out from Fig. 6.13 and Table 6.10, air-gap flux density of the aPM-FSCW and FSCW is more sinusoidal and higher than CSDW. In Appendix C, full magnetic flux distributions schemas of each designed machines are given.

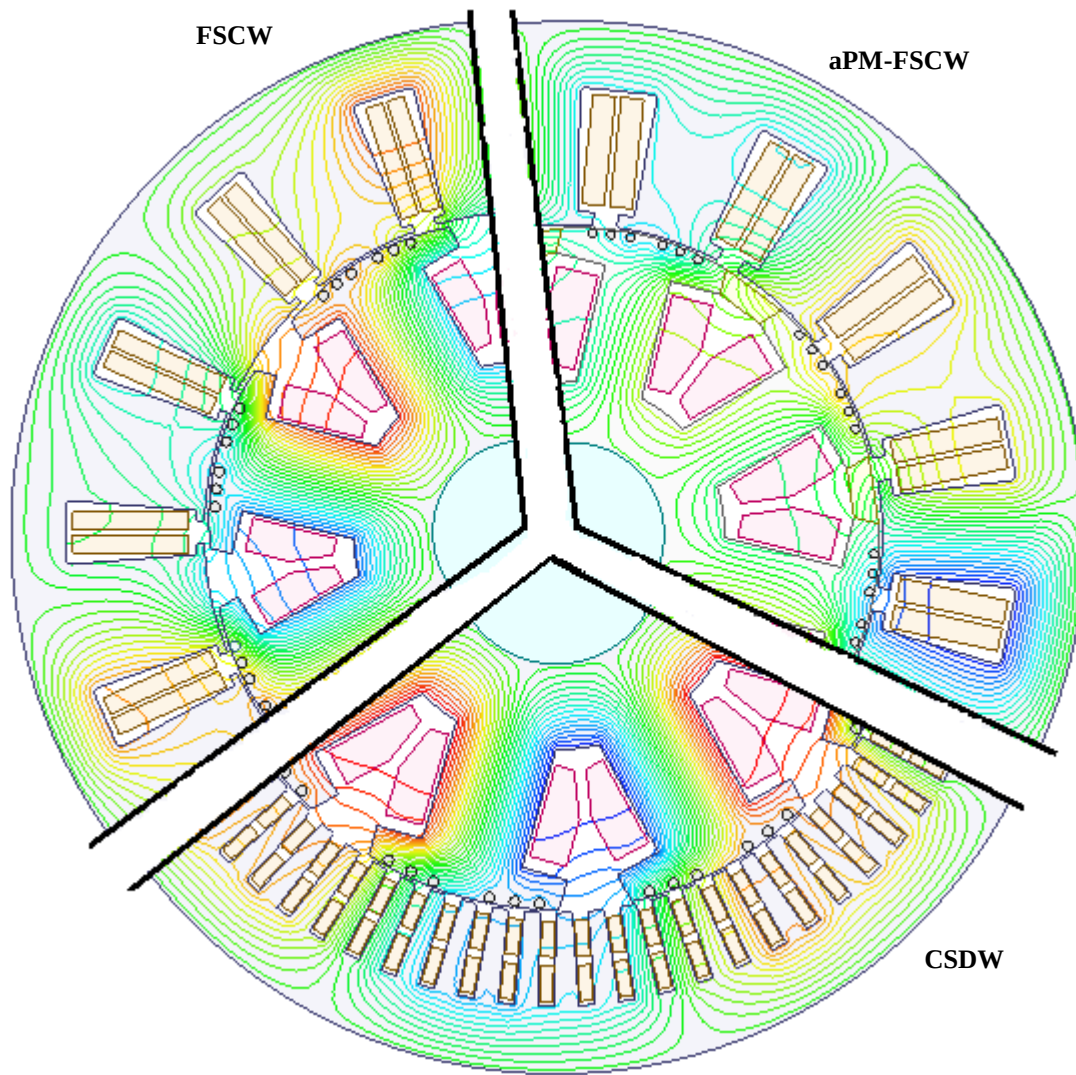


Figure 6.12: Magnetic Flux Line distribution of designed machines.

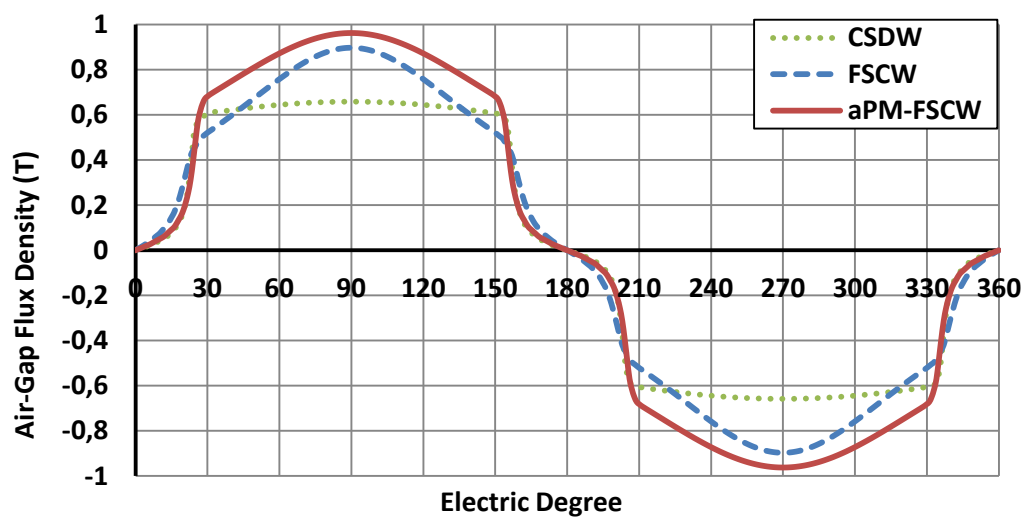


Figure 6.13: Air-gap flux densities of the designed machines.

Magnetic flux density vector distributions of designed machines given in Fig. 6.14. It is clearly seen in aPM-FSCW that PM's flux density vector directions are reverse

with field winding's flux on the pole body and same direction with stator windings' flux. As a result, it is verified that; while PM's flux are decreasing the total flux on the pole body, it is increasing the total flux in the stator core. Therefore, while saturation on the pole bodies is prevented, the induced voltage is increased. In Appendix C, full body magnetic flux vector distributions schemas of each designed machines are given.

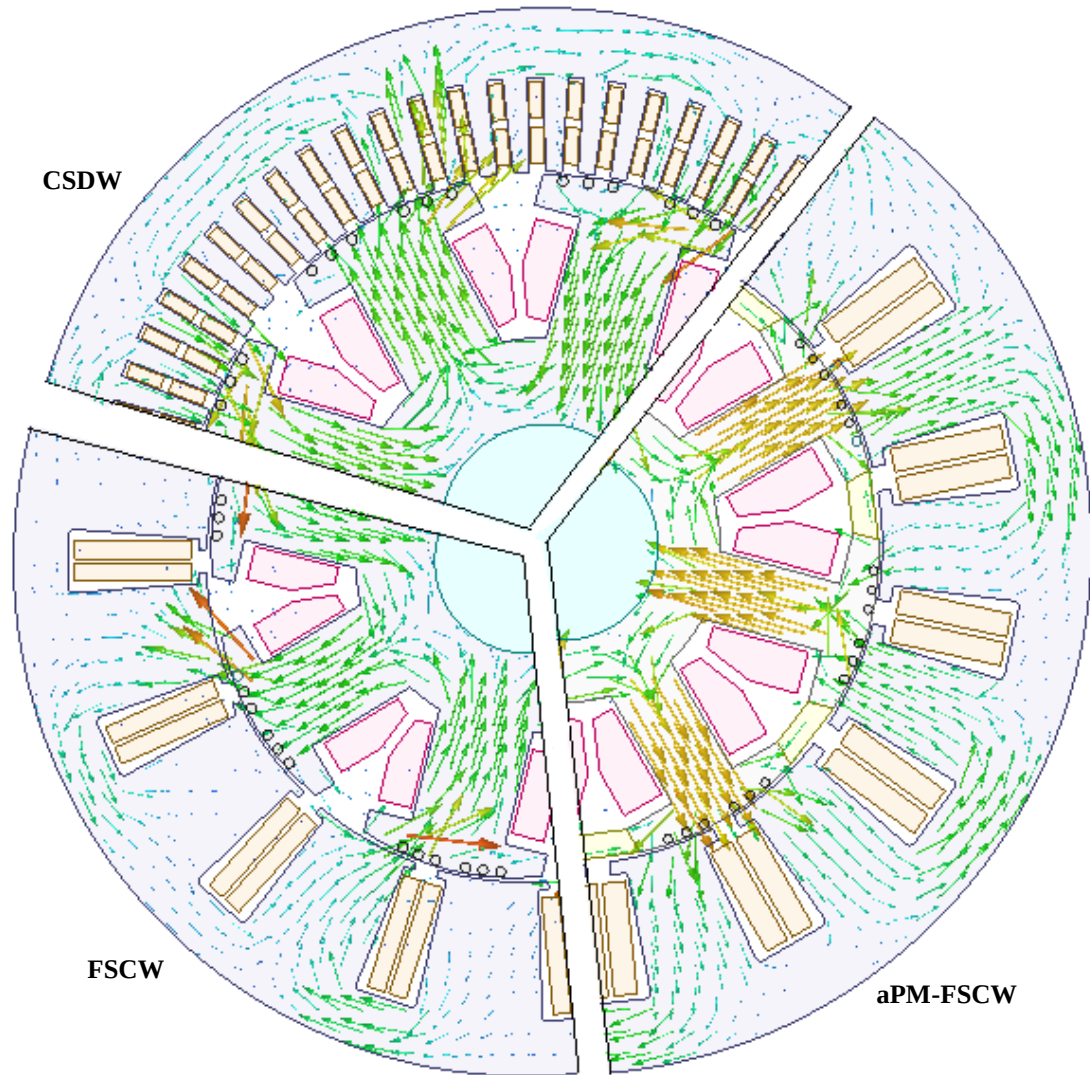


Figure 6.14: Magnetic flux vector distribution of designed machines.

After the required analysis, the results are almost same with desired results as it seen in Table 6.11 and it is substantiated that the slot leakage inductance of FSCW generators are very high according to CSDW machine having small stator slots as it shown in Fig. 6.12. These extra slot leakages may lead to more torque ripples and vibrations. Nevertheless, effect of the cogging torque and torque ripples are reduced by skewing the stator slots. And also as a result of skewing more sinusoidal induced

voltage is achieved as given in Fig. 6.6. It is verified that the cogging torque is reduced using fractional slot windings. As it mentioned in [7], using FSCW technique in large electrical machines leads to achieve high torque ripples. And it is also verified in Table 6.11. Nevertheless, designed FSCW machines operate as generator; therefore, smooth torque production is not very important issue if the acoustic noises are not so important. Additional to these, aPM-FSCW generator does not require more cooling equipment because of its 36.5% lower armature current density. As a natural result of the FSCW technique the induced voltages of the FSCW and aPM-FSCW generators are lower at the same apparent power condition because of the lower winding factor. aPM-FSCW machine has lower cogging torque and peak to peak torque ripple than FSCW machine. Because, additional PMs largely cancels the flux leakages between the pole shoes. Although, peak to peak ripple torque of the CSDW machine is the lowest, its cogging torque in two teeth is the highest. In addition, it is verified that the additional PMs have been increased the induced voltage according to FSCW generator.

Table 6.11: Full-Load Data.

Output Parameter	CSDW	FSCW	aPM-FSCW
Phase Voltage (kV)	3.81	3.81	3.81
Phase Current (A)	209.946	209	208.55
Induced Voltage (kV)	3.98	3.88	3.93
Armature Current Density (A/mm²)	5.161	4.93	3.13
Exciting Current Density (A/mm²)	3.78	4.74	4.56
Exciter Current (A)	156.192	175	169
Exciting Voltage (V)	108	100	91
Apparent Power (kVA)	2400	2389.2	2384
Cogging Torque in two teeth (N.m)	0.3	0.135	0.015
Peak to Peak Torque Ripple (kN.m)	1.67	5.467	3.25

All losses and other efficiency parameters are given in Table 6.12. As it figured out from the Fig. 6.15, approximately 50% of the total machine losses consist of copper losses. aPM-FSCW machine has less eddy current and core losses. Although aPM-FSCW generator is more lighter and designed machines have the almost same output power and efficiency, FSCW and aPM-FSCW machines can be loaded more without going to saturation according to CSDW machine. As a result of the analysis it is figured out that the stranded (eddy current) losses in the aPM-FSCW generator is 26.2% low than FSCW because of the 22% low iron core material consumption.

The efficiency of the aPM-FSCW generator which is smaller in size and lighter in weight is slightly greater, although it has same output characteristics with FSCW and CSDW generator.

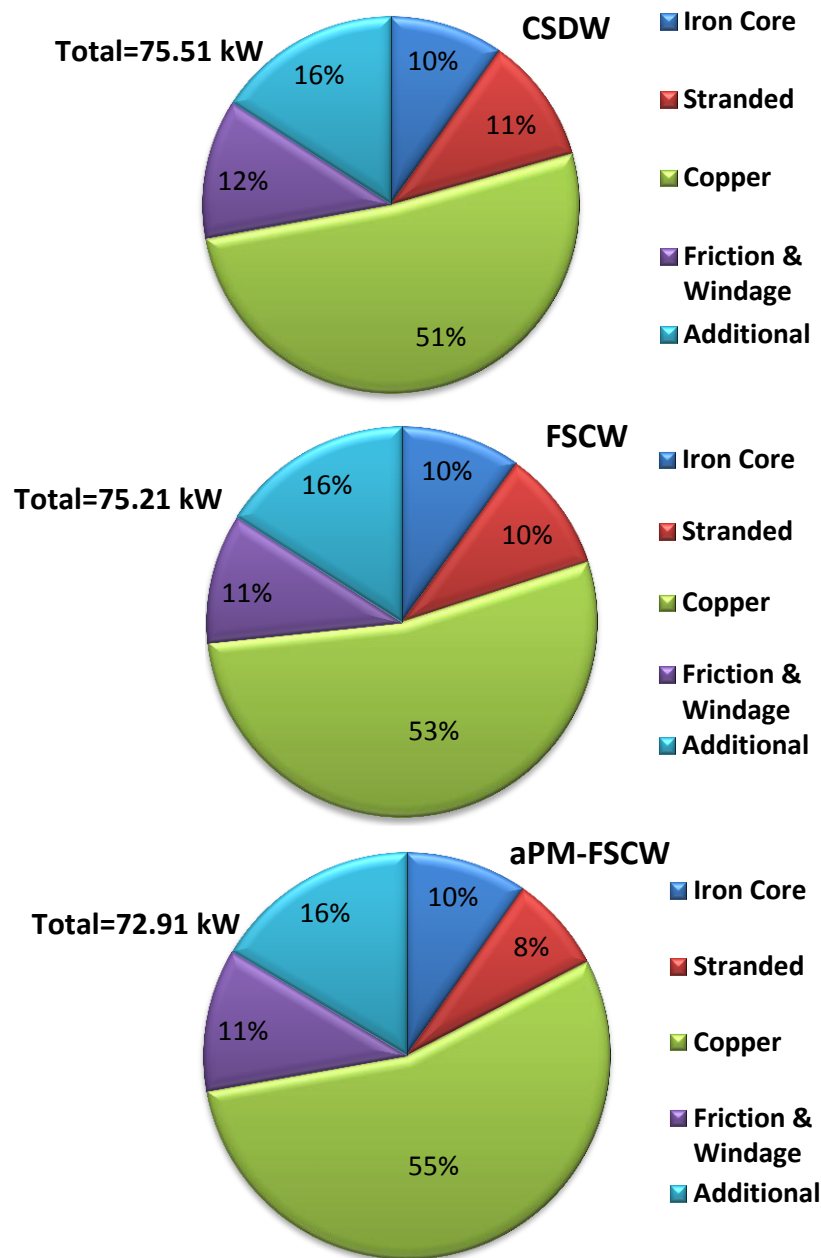


Figure 6.15: Percentage of the machine losses.

After completion of the analysis, 3D views of the generators are prepared as shown in Fig. 6.16. Furthermore, their appearances from different perspectives are given in Appendix D. While figures are examined given in Appendix D, appearance of skewed stator cores, excitations, damper windings, place of the PMs and also cooling ducts can be easily seen.

Table 6.12: Efficiency parameters.

Losses (kW) & Efficiency (%)	CSDW	FSCW	aPM-FSCW
Iron Core	7.3588	7.45	7.044
Stranded	8.1996	7.607	5.614
Copper	38.9	40.1	40
Friction & Windage	9.05	8.05	8.25
Additional	12	12	12
Total	75.5084	75.207	72.908
Power Factor	0.8	0.81	0.8
Input Power	1920	1935.24	1906.78
Output Power	1844.5	1860	1833.87
Efficiency	96.07	96.11	96.176

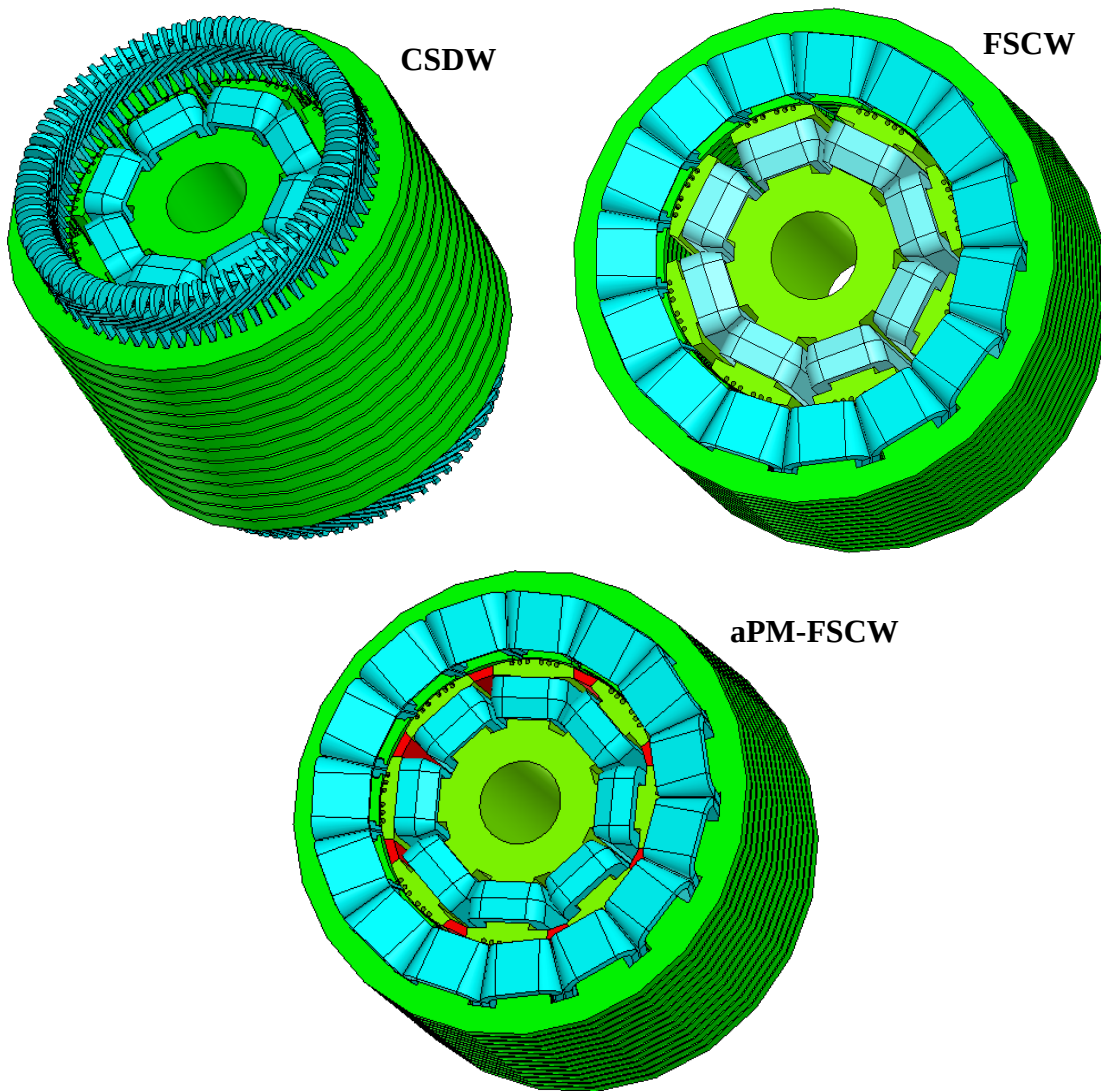


Figure 6.16: 3D views of the designed CSDW and FSCW generators.

6.3 Estimated Cost of the Active Materials

The cost of an electrical machine depends on a large number of variables. The cost can be evaluated only approximately since it depends on the number of electrical machines of the same type manufactured per year, manufacturing equipment, and organization of production process, quality of materials and other aspects and cost of labor. The most important costs of an electrical machine depend on the number of manufactured machines per annum, the cost of the winding, the cost of the ferromagnetic core and components dependent on the size of core (frame, end disks, bearings, etc.), the cost of PMs, the cost of shaft and the cost of all other components independent of the shape of the machine, e.g. nameplate, encoder, terminal board, terminal leads etc. [182]. Current prices for basic materials used in electrical machines are given in Table 6.13 and 6.14.

Table 6.13: Global Metal Prices [183].

Metal	Cost (\$/Kg)
Copper Wire Rod	8.7
Copper Bar	8.65
Copper LME CU Officials	8
Steel Cold Rolled Coil Ex-Works Turkish Port	0.845
Steel Hot-Dip Turkish Port	0.92
Steel Cold Rolled Coil FOB Brazilian Port	0.5
Steel Hot Rolled Coil FOB Brazilian Port	0.425
U.S. Midwest Hot-Rolled Coil Steel Settles	0.7

Table 6.14: Prices of the PMs used in electrical machines [184].

PM	Cost (\$/Kg)
Alnico5	12-18
Alnico8	18-24
Alnico9	18-24
SmCo24	120-150
SmCo28	120-160
NdFeB30	80-90
NdFeB35	80-100
NdFeB54	100-140

Detailed active material costs are given in Table 6.15. Although aPM-FSCW has the best design characteristics including lowest weight, highest efficiency, and etc., it is the most expensive design because of the high PM prices as it seen in Table 6.14. It is 21.267 % more expensive than FSCW generator and 13.601 % more expensive

than CSDW generator design. As it figured out from table, FSCW design is the cheapest design.

Table 6.15: Detailed Active Material Weights and Cost.

	Weigh (kg) /Cost (\$)	CSCW	FSCW	aPM-FSCW
Stator	Copper	509.565	600.55	601.496
	Copper Cost	4433.215	5227.785	5233
	Core Steel	1665.45	1560.35	1292.89
	Core Cost	1407.3	1318.5	1092.5
	Total Cost	5840.515	6546.285	6325.5
Rotor	Damper	181	153.64	109.5
	Damper Cost	1574.7	1336.7	952.65
	Copper	424.45	283.422	267.777
	Copper Cost	3692.715	2465.77	2329.6
	PM	-	-	49.085
	PM Cost	-	-	3926.8
	Core Steel	1152.95	781.656	532.437
	Core Cost	974.24	660.5	450
	Total Cost	6241.655	4463	7659
	Total Net Weight	3933.32	3379.62	2853.156
	Total Net Cost (\$)	12,082.00	11,010.00	13,984.00

In the calculation of PM cost, price per kg of the NdFeB PM material cost is supposed as \$80. It is straightforwardly deducted that if the PM price per kg is equal to or lower than \$41.24, aPM-FSCW generator design becomes favorable at this level. Labor, maintenance and repair costs, which are lower in FSCW machines, were not taken into account. If the cost of the machine is more important, selecting FSCW design will be more appropriate and economical since PM materials are more expensive than copper. If the compactness, lightness and efficiency is more important, selecting aPM-FSCW generator design will be more appropriate. Therefore, as long as the prices of the PMs stay high, the aPM-FSCW machine will cost more than SPSM in the future also.

The cost distributions of active materials for CSCW and FSCW generators are shown in Fig. 6.17. While rotor copper loss of the CSDW machine is the highest, aPM-FSCW is the lowest. Rotor core cost of the aPM-FSCW generator is the lowest because of the lowest core usage which is achieved as a result of using PMs between the pole shoes. On the other hand, cost of the PMs is accounted for more than a quarter.

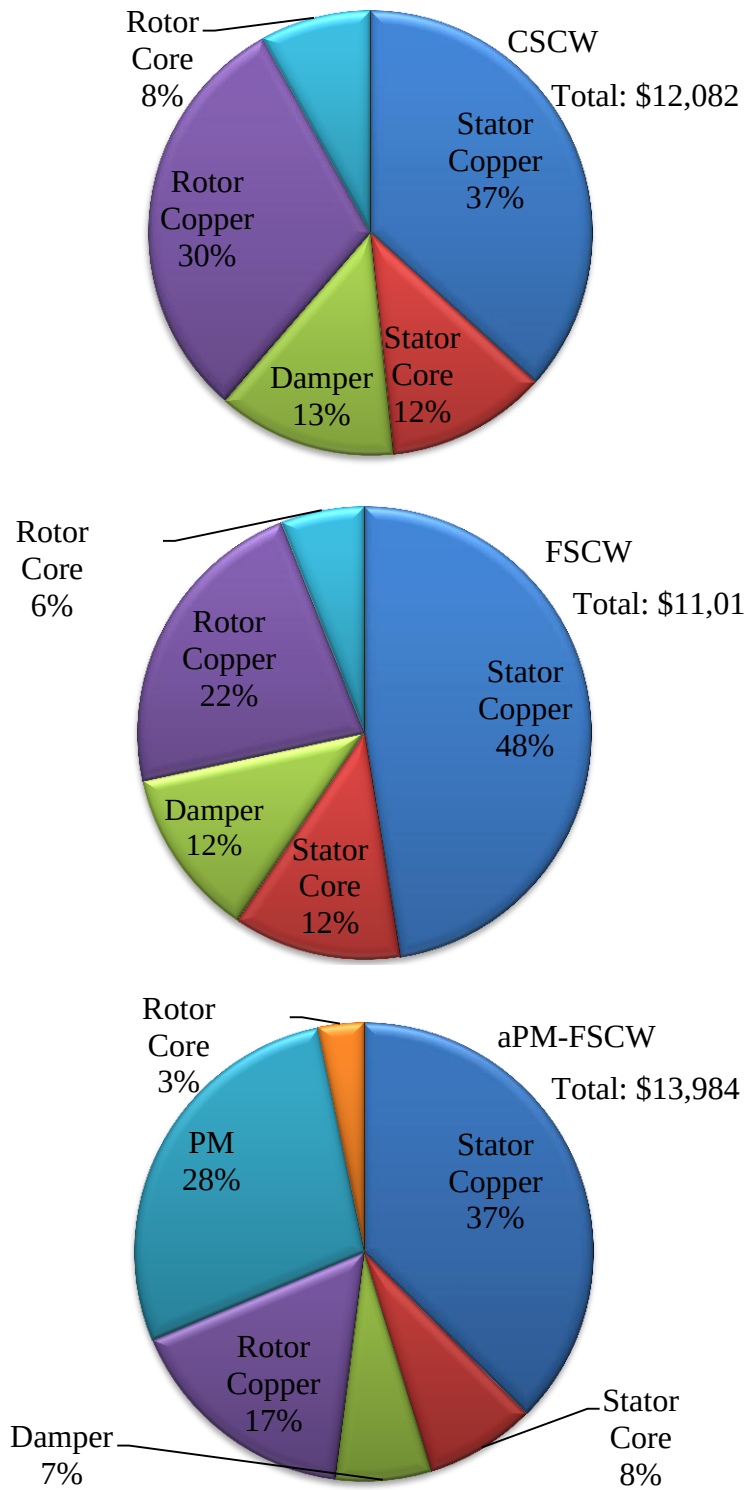


Figure 6.17: Cost percentage pie chart of active materials.

7. CONCLUSIONS AND RECOMMENDATIONS

Considering the natural energy sources of the earth are limited, it is clearly realized that the efficient use of these sources depend on a good machine design. Today, electrical machine designs are developed by widely using the PMs and concentrated windings. SPSGs are widely used in electric power generation applications as it known as well. One of the most common and important problems of these SPSGs is that their pole bodies usually go to saturation which leads to limit the output voltage and also power. This problem can be solved in two ways. One is to use FSCW topology and the other is to replace PMs between the adjacent pole shoes of the generators, which are designed by using FSCW technique. In addition, dimensions, weight and also the cost of the machine can be reduced by this FSCW technique and additional PMs.

Studies concentrated on this subject are given as a summary of the literature to be able to demonstrate the diversity of this study from other studies in the introduction. Fractional and concentrated winding topologies which are constituted the main part of this thesis are discussed in the section 2 and 3. PM's are used to develop the FSCW design. For this reason, general physical and chemical properties and also prices of the PMs used in the design of electrical machines are discussed in the section 4. Implementation of FSCW technique to large SPSGs is given in section 5 with detailed machine parameter calculation expressions. Significant developments such as increasing in the permeability of iron core and efficiency of the machine and reduction of copper usage in the stator has been observed as a result of FSCW technique which provides increasing in the flux leakages when combined with concentrated windings. Also, these significant developments are enhanced by placing PMs between the adjacent pole shoes which reduces the value of the total flux flowing on the pole body.

The objective of this thesis is to develop the SPSGs, which are mainly used in the power plants by using FSCW technique for the stator and PMs in the stator. A detailed explanation has been presented describing how concentrated windings

achieve this objective by increasing the phase inductance and how the PMs allow a reduction of the magnetic saturation in the pole bodies and pole shoes and an increase of the terminal voltage and output power. As a result of these developments, designed FSCW generator has been optimized to achieve lighter, cheaper and high efficiency SPSGs.

To be able to show the feasibility of the FSCW technique to large SPSGs 2.4MVA, 6.6kV/50Hz, 8 poles, double-layer, 15 slots FSCW and aPM-FSCW generators are designed for power plants. Moreover, a 69 slots CSDW generator which has the same output parameters is designed for comparison with FSCW and aPM-FSCW and validation of this technique. A detailed comparison including designed machines' parametric and characteristics is presented in this study. Numerical calculations for finding the accurate magnetic field density on FSCW machine eliminating any end-winding overlap with other phase windings is investigated and the mechanism of voltage increase by additional PMs in aPM-FSCW is investigated by using a nonlinear magnetic circuit. Although this circuit is very simple and the equations can be solved without any coupling with the FEM, the accuracy is nearly identical to that of the FEM. Proportions of the rotor and stator components to the total flux produced by the PMs were investigated by linear FEA with frozen permeability. The basic characteristics and the magnetic flux distributions in the FSCW and aPM-FSCW SPSGs of the same output power are compared by FEA.

The main conclusion of this study is that SPSMs can be designed to achieve lighter, cheaper and high-efficiency SPSGs with more simple structure and poles with high permeability without reducing the output power by performing FSCW technique to SPSG's stator. Results presented in this paper open the door to developing SPSM designs and these results are intended to provide useful guidelines for engineers faced with reducing the saturation of the generator poles without reducing the efficiency and optimal design of the machine. Additional to these results, Table 7.1 has been given to be able to indicate the numerical values of the results that achieved as a result of comparison of CSDW and aPM-FSCW machines.

Results presented in this study show that output characteristics and the compactness of the SPSGs can be improved via FSCW technique developed by PMs. And these results are intended to provide useful guidelines for engineers faced with reducing

the saturation of the generator poles and optimization of the machine without reducing the efficiency.

Table 7.1: Numerical comparison of achieved results.

Parameter	CSDW	FSCW	%	aPM-FSCW	%
Total Weight (kg)	3933.32	3379.62	-14.077	2853.156	-27.46
Armature Leakage Reactance (Ω)	4.57	27.38	+500	30.66	+570.9
Flux Density on Pole-Body (T)	1.7	1.31	-22.941	0.95	-44.11
Efficiency (%)	96.07	96.11	+0.041	96.176	+0.11
Armature Resistance (Ω)	0.29	0.3	+0.345	0.3	+0.345
Field Winding Resistance (Ω)	0.7	0.57	-18.57	0.54	-22.86
Total Cost (\$)	12,082	11,010	-8.872	13,984	+15.74

*(-) indicates the decrease and *(+) indicates the increase according to CSDW generator.

Theoretical predictions based on simplified analyses and finite element analyses have been validated. One of the observations is that FSCW machines in which alternate teeth are wound have a significantly higher inductance due to the much higher slot leakage component.

On the other hand, if the cost is more important instead of efficiency, compactness and also total weight, selecting the FSCW generator will be more appropriate. In addition to this, unless the demand for PM decreases throughout the world and China, who plays the largest role in the PM production and the market, change their decisions on the quota for export of PMs, the use of PMs in the design of electrical machines will be at a disadvantage in the manner of cost. Nevertheless, if the PM prices decrease down to \$41.24 per kg for this study, their usage in the design of SPSGs will be advantageous. Therefore, this study displays that by means of generators produced with a better machine design and using windings instead of PMs, clean energy can be generated cheaper and more efficiently. In addition, while $BH_{\max}$ capacity of a PM material is increased up and the flux distribution and magnetic field strengths of this developed PM materials are modeled properly, it is possible to design smaller and more economical machines. Wherever small size and low weight are needed, rare earth magnets are a necessity. And also to design a machine with optimum efficiency, the correct selection of the magnet material, size, and shape is very important. Moreover, new applications and design concepts are evolving and electrical machines and other devices are becoming further miniaturized as a result of broader use of magnets. The demand for magnets will remain large unless alternative technologies and materials prevail.

Key results include:

- ✓ Standard winding factor is developed by experimental combination of pitch and distribution factors using the large range of available space.
- ✓ FSCW and aPM-FSCW designs offer opportunities to minimize machine volume and mass because of their short winding end turns and techniques for achieving high slot fill factors.
- ✓ FSCW design according to CSDW and aPM-FSCW design according to FSCW design offer opportunities to minimize machine volume preventing saturation of the rotor pole-bodies (in other words increasing the permeability of the iron core).
- ✓ Core and also eddy (stranded) losses are reduced.
- ✓ Higher efficiency was achieved without reducing the output power.
- ✓ Conventional SPSGs will become easy to maintenance by designing it by FSCW technique (simplifying the CSDW generator's complex structure).

On the other hand, the problematic and incomplete aspects of this study are summarized as follows.

- Increase in the torque ripples.
- Increase in the total cost of the aPM-FSCW because of the very high PM prices.
- To manufacture of the prototypes according to designs and comparison of simulation results and prototype measurements.

As future works of this study, using different types of PM materials and iron core materials, segmented PMs or PMs having different shapes and conducting better machine design, the designed machines can be developed. Furthermore, heat analysis of the designs may be conducted to support the designs.

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APPENDICES

APPENDIX A: Magnetic flux densities at full-load generator operation.

APPENDIX B: Relative permeabilities at full-load generator operation.

APPENDIX C: Magnetic flux and vector line distributions at full-load generator operation.

APPENDIX D: 3D views of the designed generators.

APPENDIX E: Electrical steels (M39_29G) properties of used iron core in the design.

APPENDIX F: Types of Surface Insulation Resistance and Typical Applications.

APPENDIX G: NdFeB35 PM datasheet.

APPENDIX H: Copper properties used in the field and stator winding designs.

APPENDIX A

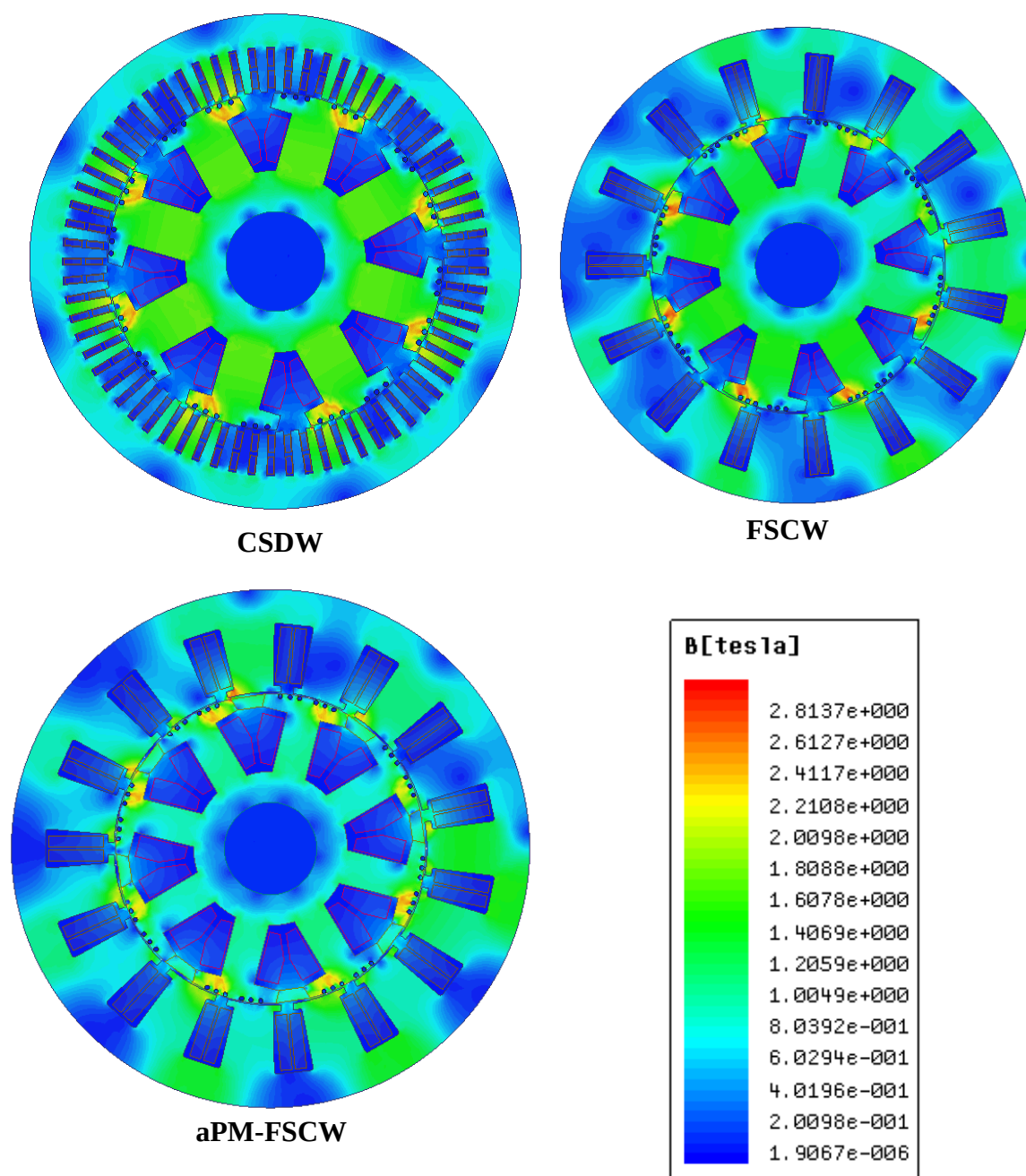


Figure A.1 : Magnetic flux density of the designed generators at full-load.

APPENDIX B

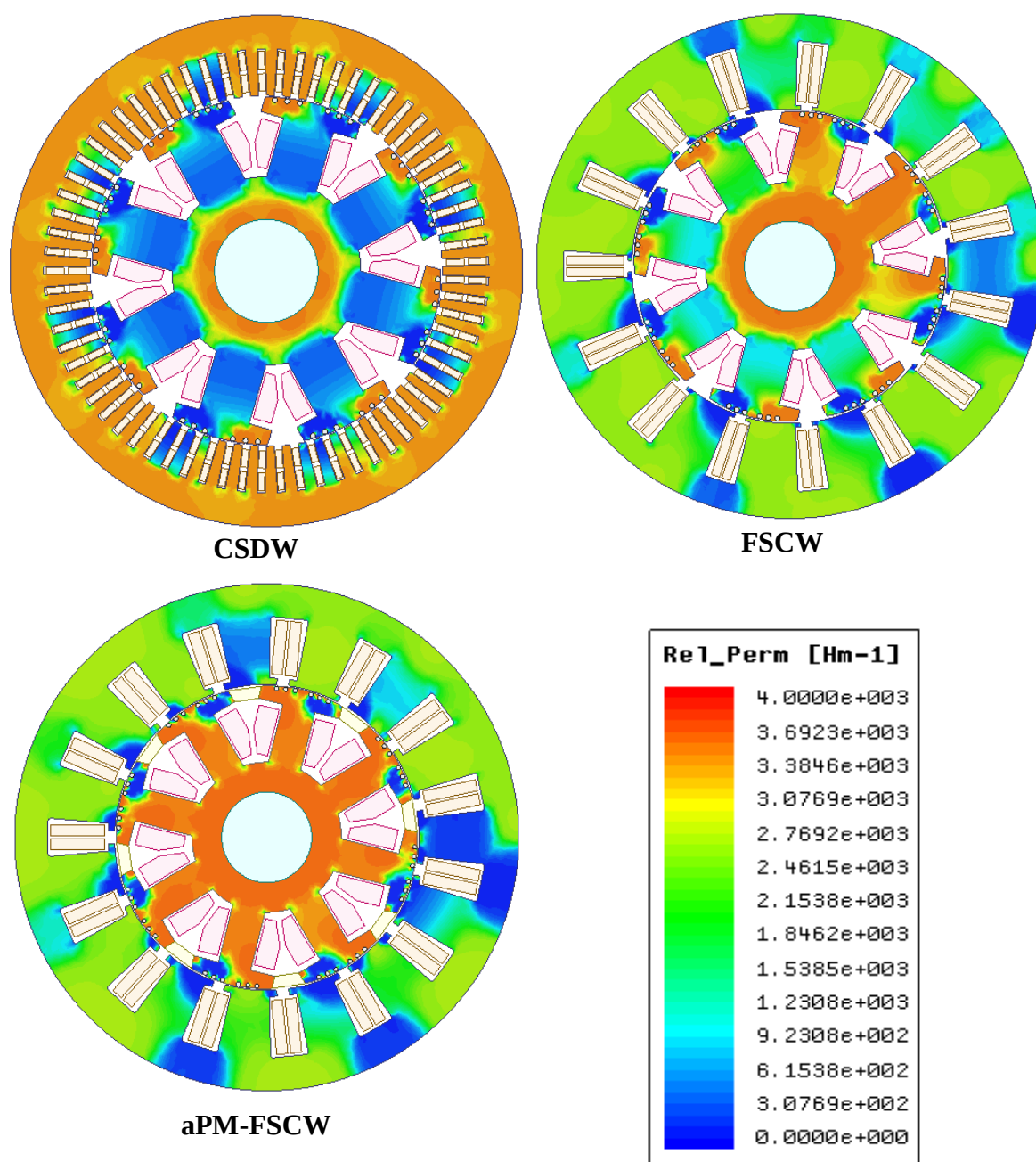
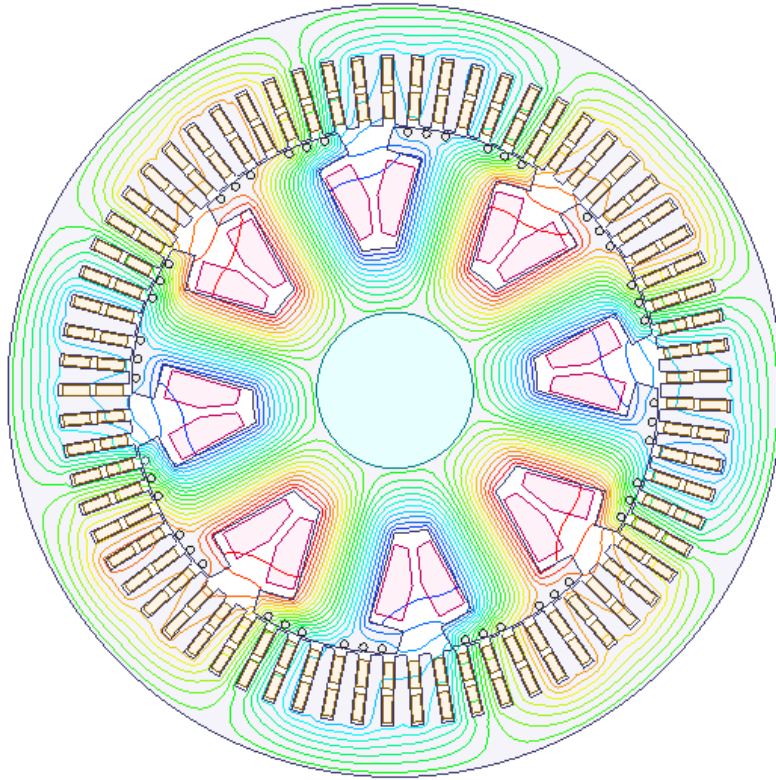
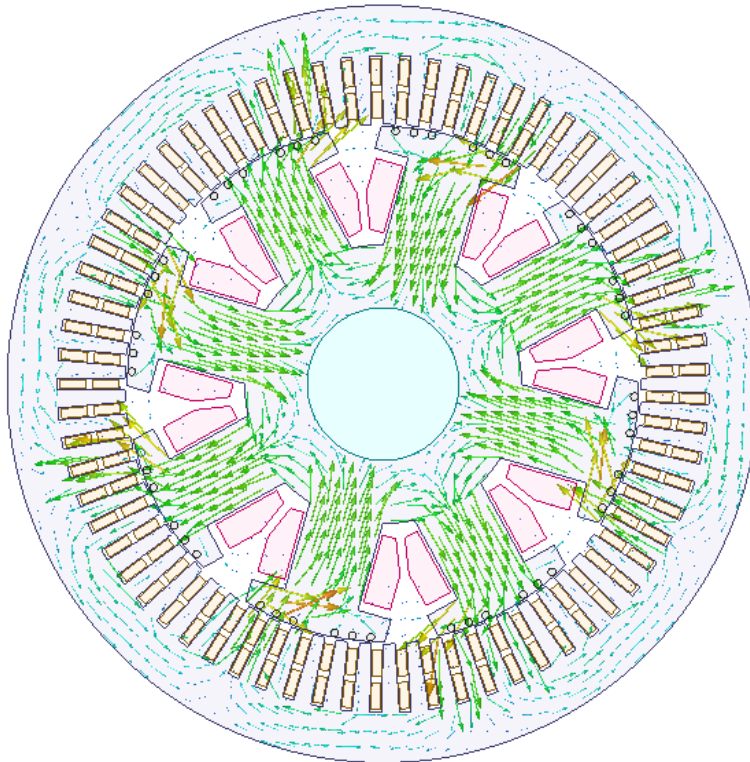


Figure B.1 : Relative permeability of the designed generator at full-load.

APPENDIX C

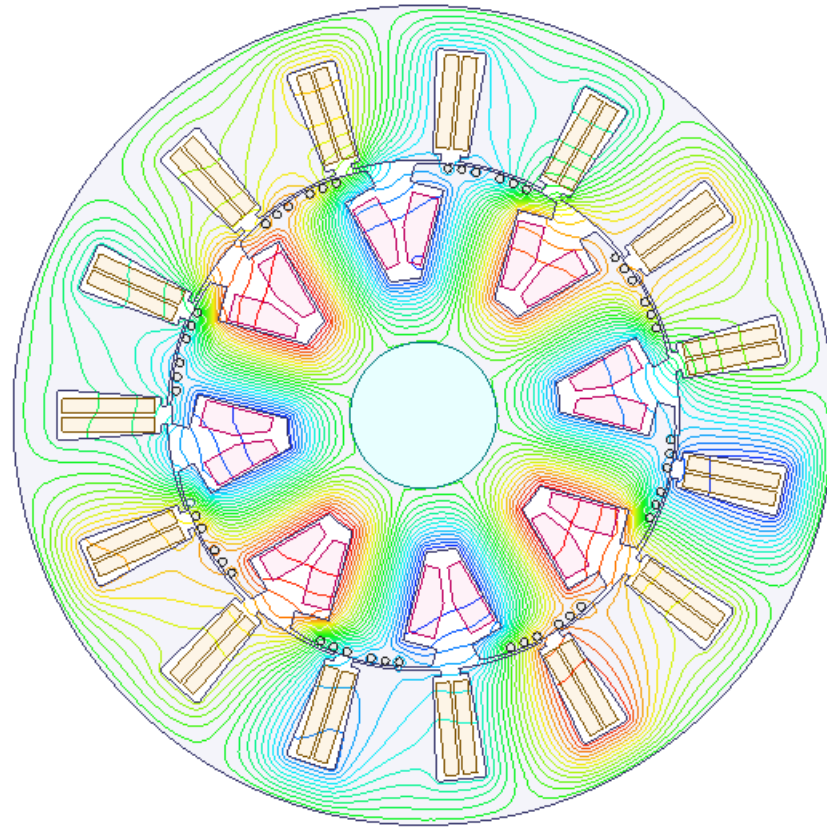


(a)

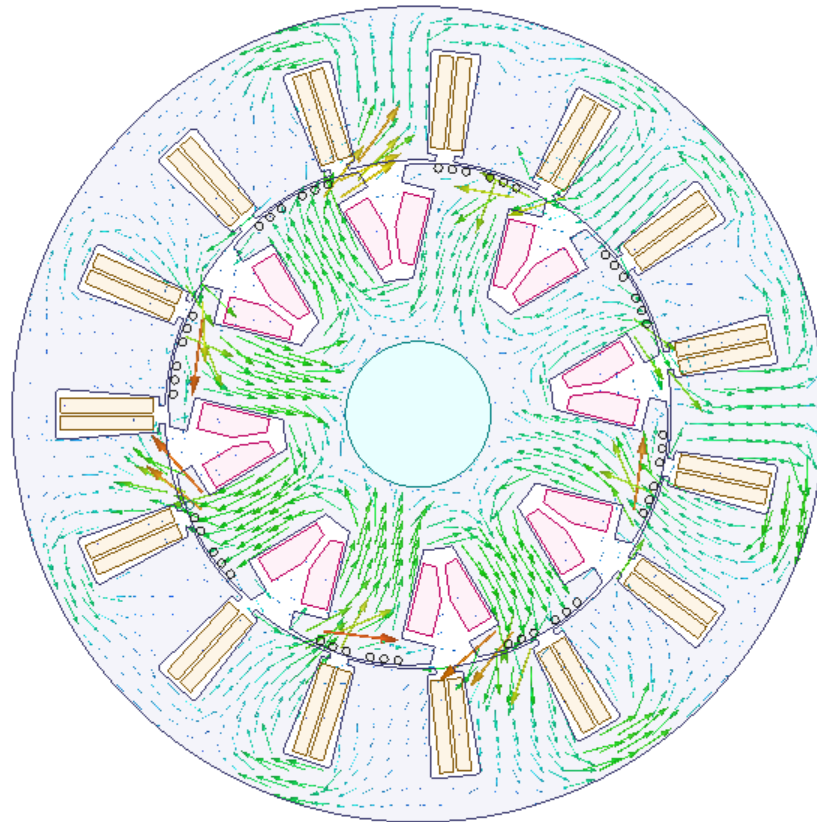


(b)

Figure C.1 : Magnetic flux line (a) and vector (b) distribution of CSDW generator at full-load.

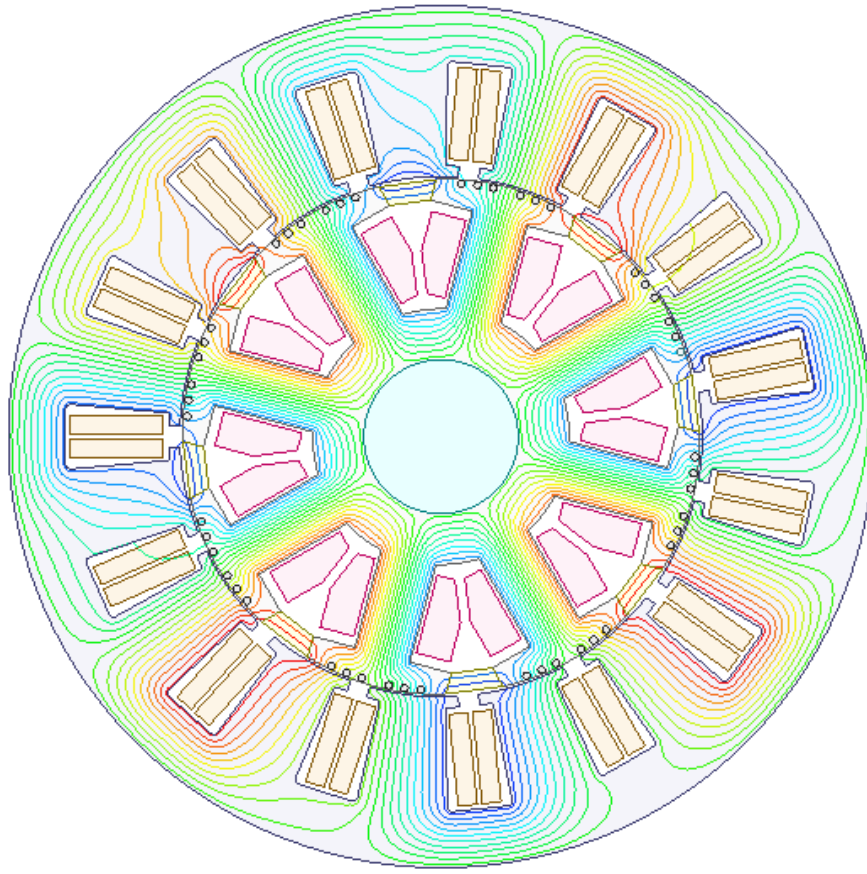


(a)

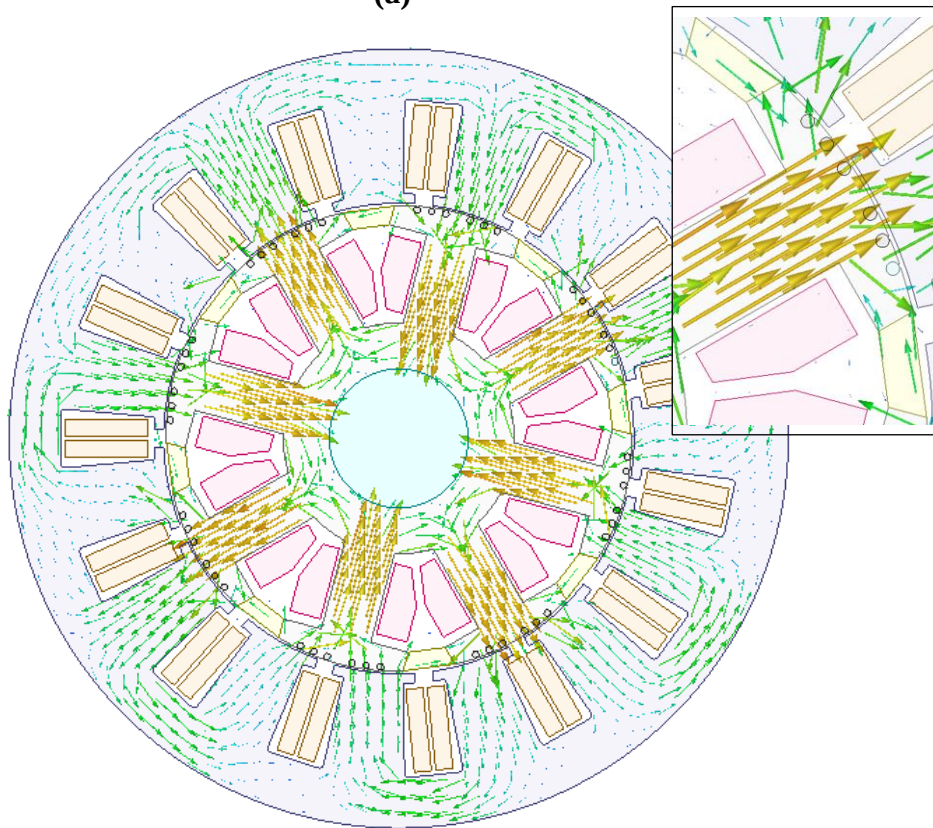


(b)

Figure C.2 : Magnetic flux line (a) and vector (b) distribution of FSCW generator at full-load.



(a)



(b)

Figure C.3 : Magnetic flux line (a) and vector (b) distribution of aPM-FSCW generator at full-load.

APPENDIX D

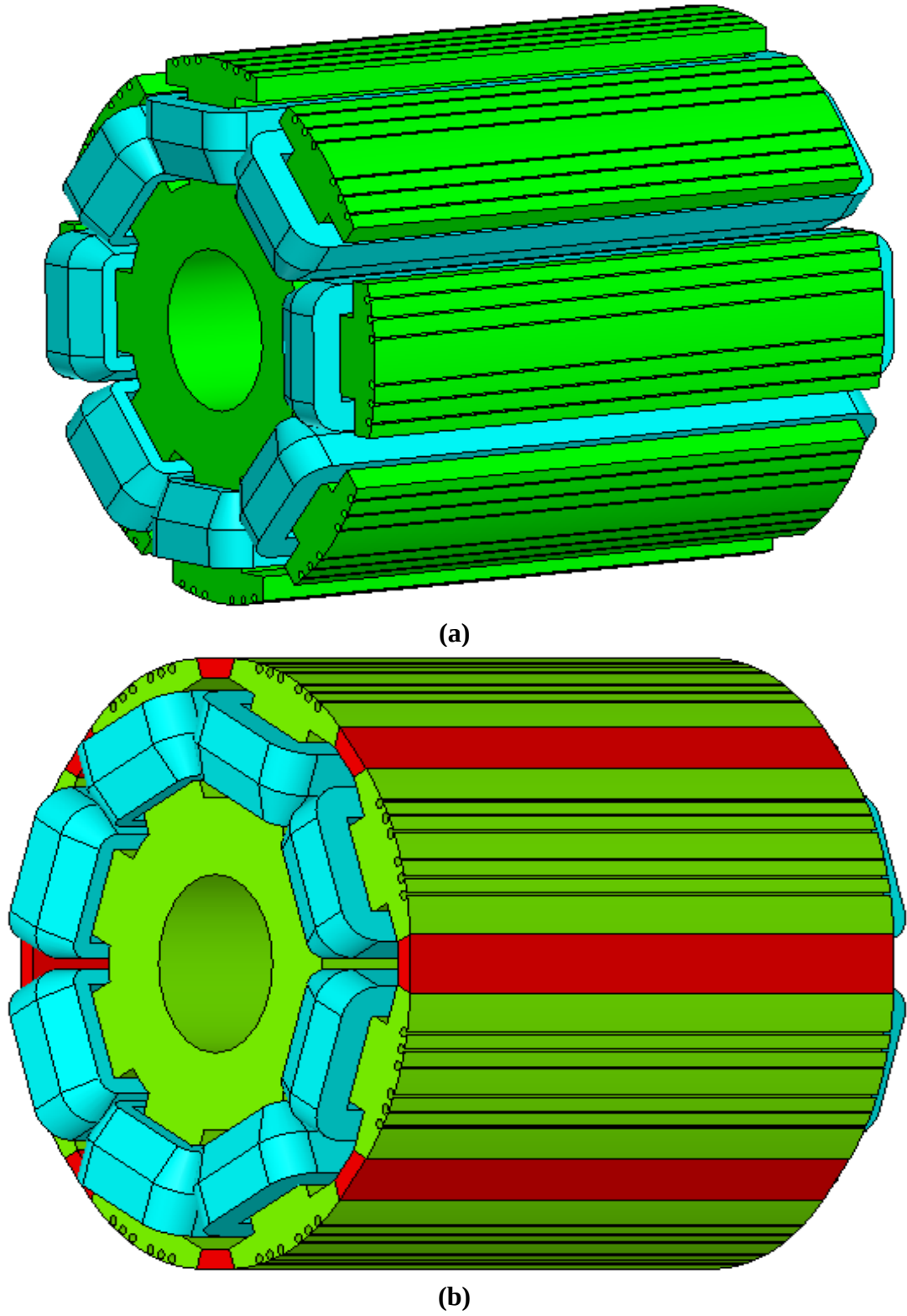


Figure D.1 : 3D views rotor of (a) CSDW and FSCW generators and (b) aPM-FSCW generator.

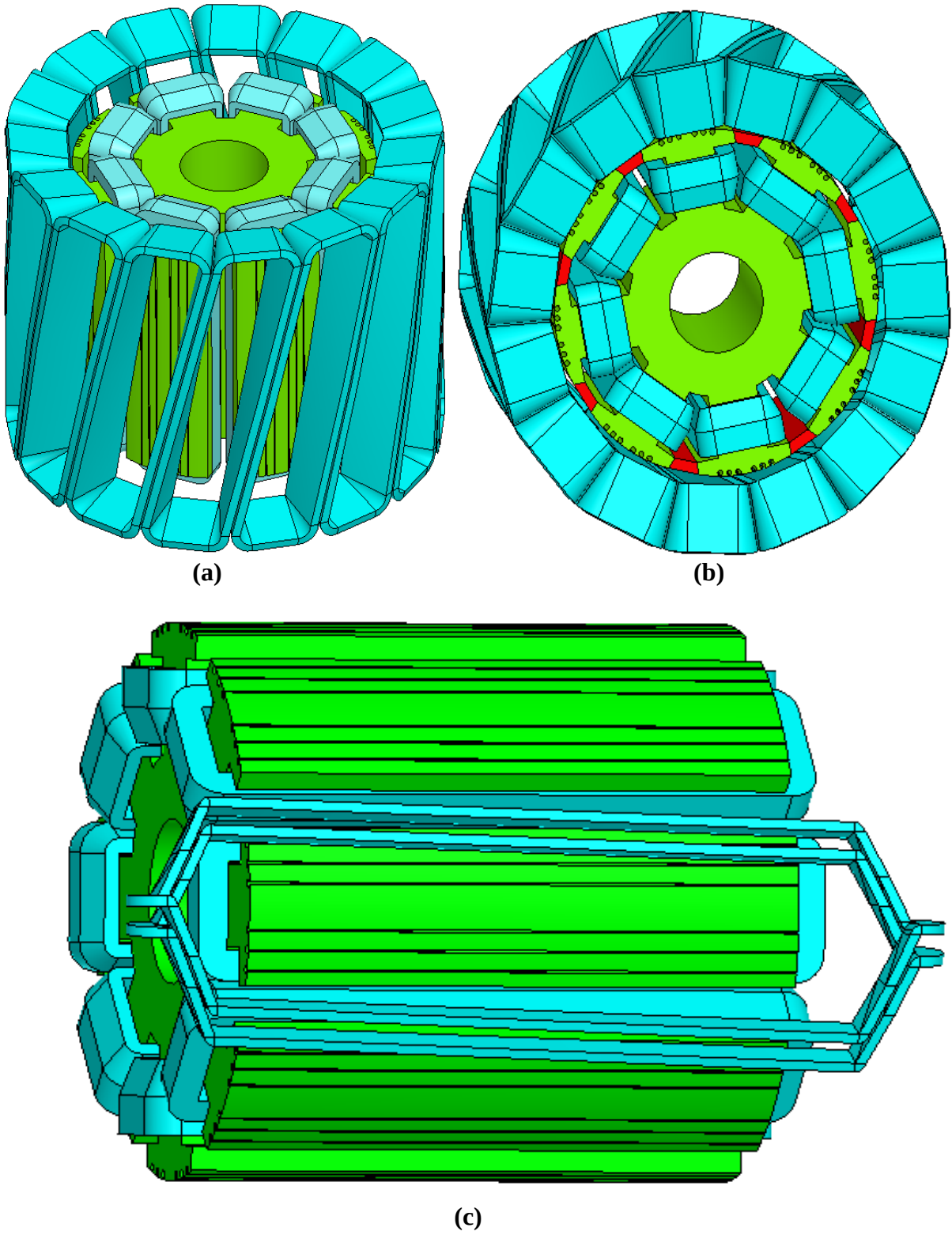
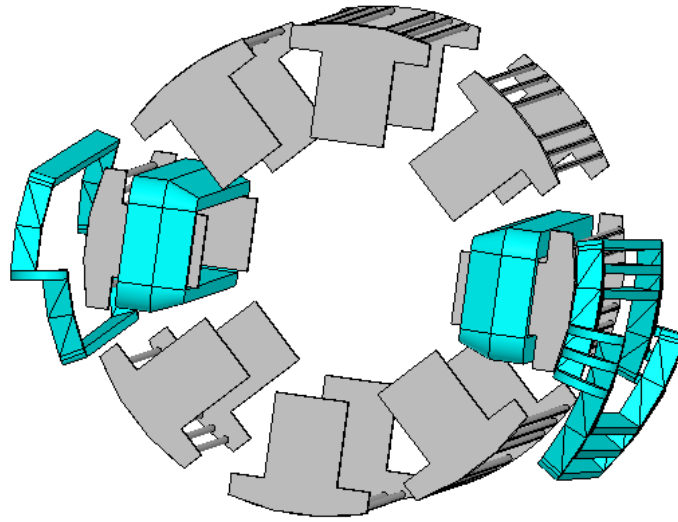
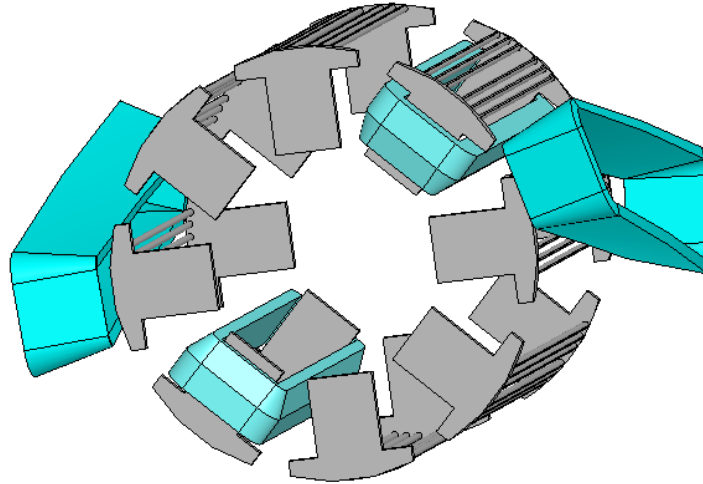


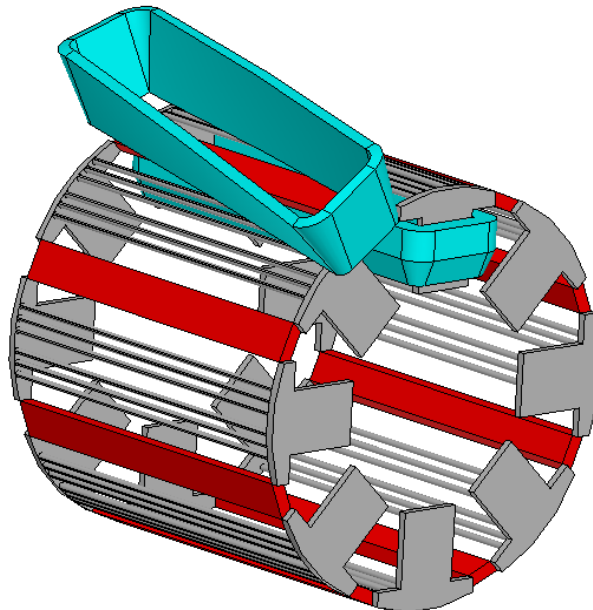
Figure D.2 : 3D views; (a) complete rotor and stator winding of FSCW design, (b) aPM-FSCW design, and (c) CSDW design.



(a) CSDW

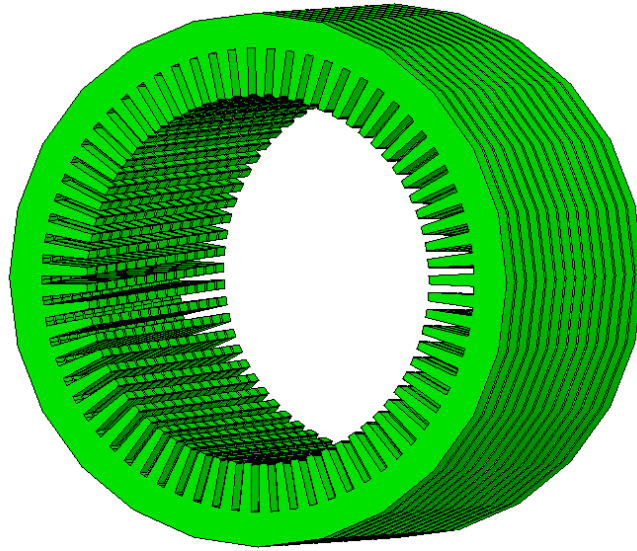


(b) FSCW

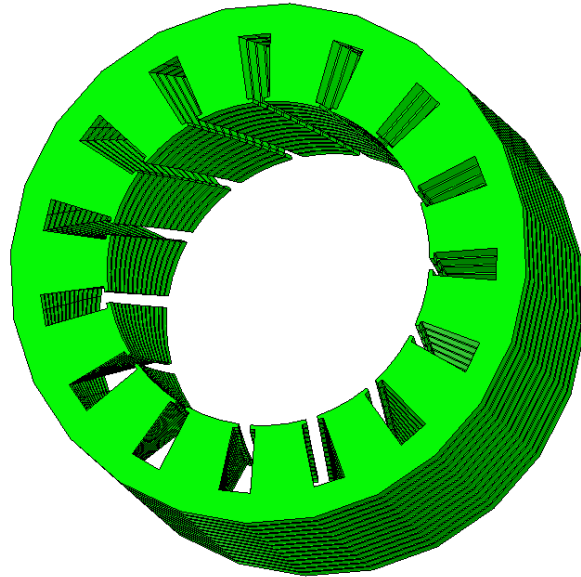


(c) aPM-FSCW

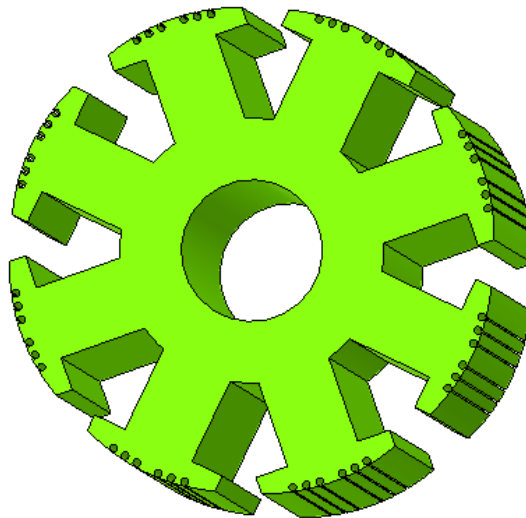
Figure D.3 : 3D views of damper, stator and filed windings of designed machines.



(a) Stator core of CSDW



(b) Stator core of FSCW and aPM-FSCW



(c) Rotor core of designed machines

Figure D.4 : 3D views of stator and rotor cores of designed machines.

APPENDIX E

Table E.1 : Core Loss Limits for Electrical Steels.

AK Steel Grade	Nominal Thickness in. (mm)	Electrical Steel Std. Gage	Core Loss at 60 Hertz - Watts per Pound*		
			15 kilogausses		17 kilogausses
			Fully Processed As-Sheared	Semi-Processed Quality Annealed†	Fully Processed As Sheared
TRAN-COR					
H-0	.009 (.23)	—	—	—	.60**
H-1	.011 (.27)	—	—	—	.66**
H-0 DR	.009 (.23)	—	.39***	—	.535***
H-1 DR	.011 (.27)	—	.425***	—	.57***
Oriented					
M-2	.007 (.18)	—	.405**	—	—
M-3	.009 (.23)	—	.445**	—	.70**
M-4	.011 (.27)	—	.51**	—	.74**
M-6	.014 (.35)	—	.66**	—	.94**
Nonoriented					
M-15	.014 (.35)	29	1.45	—	—
	.0185 (.47)	26	1.60	—	—
M-19	.014 (.35)	29	1.55	—	—
	.0185 (.47)	26	1.65	—	—
	.025 (.64)	24	2.00	—	—
M-22	.014 (.35)	29	1.60	—	—
	.0185 (.47)	26	1.80	—	—
	.025 (.64)	24	2.10	—	—
M-27	.014 (.35)	29	1.75	—	—
	.0185 (.47)	26	1.90	—	—
	.025 (.64)	24	2.25	—	—
M-36	.014 (.35)	29	1.85	—	—
	.0185 (.47)	26	2.00	—	—
	.025 (.64)	24	2.35	—	—
M-43	.014 (.35)	29	1.95	—	—
	.0185 (.47)	26	2.10	1.55	—
	.025 (.64)	24	2.50	2.00	—
M-45	.0185 (.47)	26	2.40	—	—
	.025 (.64)	24	2.75	—	—
M-47	.0185 (.47)	26	2.80	1.65	—
	.025 (.64)	24	3.20	2.10	—

*Core loss tests are conducted in accordance with ASTM A 343 and A 804. For the nonoriented grades, tests are made on 3-cm-wide Epstein strips sheared half parallel and half transverse to the rolling direction.

**The core loss limits for the grain-oriented grades M-2, M-3, M-4, M-6 and TRAN-COR H-0 and H-1 are for parallel grain Epstein specimens given a stress-relieving anneal after cutting from fully processed steel.

***Core loss limits for H-0 DR and H-1 DR are for parallel grain wide sheet specimens.

†With anti-stick coating.

Table E.2 : Electrical steels mechanical properties.

Steel Grade Designation	Density gm/cm ³	Electrical Resistivity Microhm-cm	Ultimate Tensile Strength psi (MPa)	Yield Strength psi (MPa)	Elongation % in 2" (50 mm)	Hardness Rockwell B	Modulus of Elasticity
TRAN-COR and H-1	7.65	50	52,000 (359)	50,000 (345)	11	83	The modulus of elasticity will depend largely upon the grain orientation. In the following, the modulus is expressed in millions of pounds per square inch: M-6 Parallel – 18 Transverse = 29
Oriented M-2 to M-6	7.65	51	51,000 (352)	48,000 (331)	9	81	
M-15 FP	7.65	50	71,000 (490)	52,000 (358)	23	72	
M-36 FP	7.70	43	63,000 (434)	42,000 (290)	30	64	
M-47 FP	7.75	37	62,000 (427)	39,000 (269)	34	61	
M-43 SP	7.70	43	70,000 (483)	50,000 (345)	32	64	
M-47 SP	7.75	37	67,000 (462)	48,000 (331)	33	62	

Table E.3 : Materials of Similar Core Loss.

Grade	EGS Gauge No.	Normal Thickness Inches	Core Loss Watts per Pound Maximum
M-36	29	0.014	1.85
M-27	26	0.0185	1.90
M-19	23	0.025	2.0

APPENDIX F

Table F.1 : Types of Surface Insulation Resistance and Typical Applications.

AISI Insulation Designation	Description	Typical Applications
C-O	The natural oxide surface which occurs on flat-rolled silicon steel which gives a slight but effective insulation layer sufficient for most small cores and will withstand normal stress-relief anneal of finished cores by controlling the atmosphere to be more or less oxidizing to the surface.	Fractional horsepower motors, pole pieces and relays, small communication transformers and reactors.
C-2	An inorganic insulation which consists of a glass-like film which forms during high temperature hydrogen anneal of grain-oriented silicon steel as the result of the reaction of an applied coating of MgO and silicates in the surface of the steel. This insulation is intended for air-cooled.	Wound-core, power frequency devices, distribution transformers, saturable reactors and large magnetic amplifiers.
C-3	An enamel or varnish coating intended for air-cooled or oil immersed cores. The interlamination resistance provided by this coating is superior to the C-1 typed coating which is primarily utilized as a die lubricant. The C-3 coating will also enhance punchability; is resistant to normal operation temperatures; but will not withstand stress-relief annealing.	Air-cooled, medium-sized power and distribution transformers; medium-sized continuous duty, high efficiency rotating machinery. Can be oil-cooled.
C-4	A chemically treated or phosphate surface intended for air-cooled or oil-immersed cores requiring moderate levels of insulation resistance. It will withstand stress-relief annealing and serve to promote punchability.	Applications requiring insulation similar to C-3 and a stress-relief anneal. Used extensively for small stamped laminations that require higher resistance than provided by annealing oxides.
C-5	An inorganic insulation similar to C-4 but with ceramic fillers added to enhance the interlaminar resistance. It is typically applied over the C-2 coating on grain-oriented silicon steel. Like C-2, it will withstand stress-relief annealing withstand stress-relief annealing atmosphere. (For Fully Processed Non-oriented Electrical Steels).	Principally intended for air-cooled or oil-immersed cores which utilize sheared laminations and operate at high volts per turn. Also finds applications in apparatus requiring high levels of interlaminar resistance.

APPENDIX G

Table G.1: Magnetic Properties of widely used PMs.

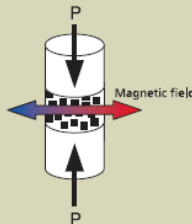
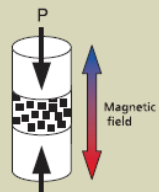
Pressing Method	Material Code	Remanence Br		Coercivity				Max BH Product (BH) max.		Temp.Coeff.Of Br	Temp.Coeff.Of H _{cJ}	Thermal Expansion Coeff	
				H _{ca}		H _{cJ}						1/K	
		T	kG	kA/m	kOe	kA/m	kOe	kJ/m ³	MGOe	%/K	%/K	C/°1	C.°2
Perpendicular  The Magnetic field is Perpendicular to the Direction of the Press Direction	NMX-S54	1.45~1.51	14.5~15.1	939~1153	11.8~14.5	≥875	≥11	405~437	51~55	-0.11	-0.60	6.3	-1.5
	NMX-S52	1.42~1.48	14.2~14.8	835~994	10.5~12.5	≥875	≥11	389~421	49~53		-0.59		
	NMX-S50BH	1.39~1.45	13.9~14.5	1042~1122	13.1~14.1	≥1114	≥14	374~405	47~51		-0.58		
	NMX-S49CH	1.36~1.43	13.6~14.3	1018~1106	12.8~13.9	≥1273	≥16	358~397	45~50		-0.55		
	NMX-S45SH	1.30~1.37	13.0~13.7	970~1058	12.2~13.3	≥1671	≥21	326~366	41~46	-0.10	-0.52	6.4	-1.7
	NMX-S43SH	1.28~1.35	12.8~13.5	962~1042	12.1~13.1	≥1830	≥23	310~350	39~44		-0.50		
	NMX-S41EH	1.24~1.31	12.4~13.1	923~1018	11.6~12.8	≥1990	≥25	294~334	37~42		-0.48		
	NMX-S38EH	1.19~1.27	11.9~12.7	883~978	11.1~12.3	≥2228	≥28	270~310	34~39		-0.47		
	NMX-S36UH	1.16~1.24	11.6~12.4	883~962	11.1~12.1	≥2387	≥30	254~294	32~37	-0.09	-0.44	6.5	-1.9
	NMX-S34GH	1.12~1.20	11.2~12.0	859~939	10.8~11.8	≥2626	≥33	238~278	30~35		-0.60		
	NMX-50	1.39~1.45	13.9~14.5	835~1034	10.5~13.0	≥875	≥11	374~405	47~51	-0.11	-0.59	6.3	-1.5
	NMX-48BH	1.36~1.42	13.6~14.2	1018~1098	12.8~13.8	≥1114	≥14	358~389	45~49		-0.58		
	NMX-46CH	1.33~1.39	13.3~13.9	994~1074	12.5~13.5	≥1273	≥16	342~374	43~47		-0.57		
	NMX-44CH	1.30~1.36	13.0~13.6	978~1058	12.3~13.3	≥1273	≥16	326~358	41~45		-0.55		
	NMX-43SH	1.27~1.34	12.7~13.4	947~1026	11.9~12.9	≥1671	≥21	310~350	39~44	-0.10	-0.50	6.4	-1.7
	NMX-41SH	1.24~1.31	12.4~13.1	923~1002	11.6~12.6	≥1671	≥21	294~334	37~42		-0.48		
	NMX-39EH	1.20~1.28	12.0~12.8	915~994	11.5~12.5	≥1990	≥25	278~318	35~40		-0.46		
	NMX-36EH	1.16~1.24	11.6~12.4	883~962	11.1~12.1	≥2228	≥28	254~294	32~37		-0.09		
	NMX-33UH	1.10~1.18	11.0~11.8	835~915	10.5~11.5	≥2387	≥30	230~270	29~34	-0.09	-0.46	6.5	-1.9
Parallel  The Magnetic Field is Parallel to the Direction of the Press Direction	NMX-44	1.29~1.36	12.9~13.6	835~1018	10.5~12.8	≥875	≥11	318~358	40~45	-0.11	-0.60	6.3	-1.5
	NMX-42BH	1.26~1.34	12.6~13.4	931~1026	11.7~12.9	≥1114	≥14	302~342	38~43		-0.59		
	NMX-40CH	1.21~1.30	12.1~13.0	915~1010	11.5~12.7	≥1273	≥16	278~326	35~41		-0.57		
	NMX-37SH	1.17~1.26	11.7~12.6	875~978	11.0~12.3	≥1671	≥21	262~310	33~39	-0.10	-0.55	6.4	-1.7
	NMX-34EH	1.10~1.20	11.0~12.0	827~931	10.4~11.7	≥1990	≥25	230~278	29~35		-0.48		
	NMX-31UH	1.06~1.16	10.6~11.6	795~899	10.0~11.3	≥2387	≥30	206~254	26~32	-0.09	-0.46	6.5	-1.9

Table G.2: Physical and Magnetic properties of widely used PMs.

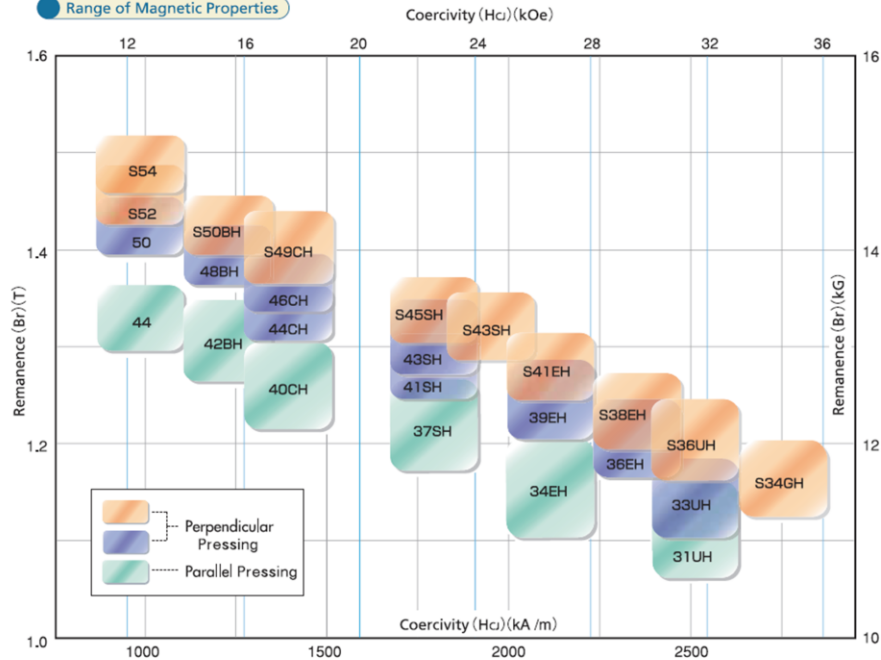
Physical Characteristics (Central value)

Items	Unit	Value
Relative Recoil Permeability	—	1.05
Specific Heat	(C)	J/kg·K
Thermal Conductivity	(C//) ^{*1} (C⊥) ^{*2}	W/m·K
Flecural Strength	(B.S)	MPa
Young's Modulus	(E)	GPa
Rigidity	(G)	GPa
Vickers Hardness	—	Hv
Electric resistivity	(C//) ^{*1} (C⊥) ^{*2}	μΩ·m
Density	(ρ)	kg/m ³ ×10 ³
Curie Temperature	(Tc)	K

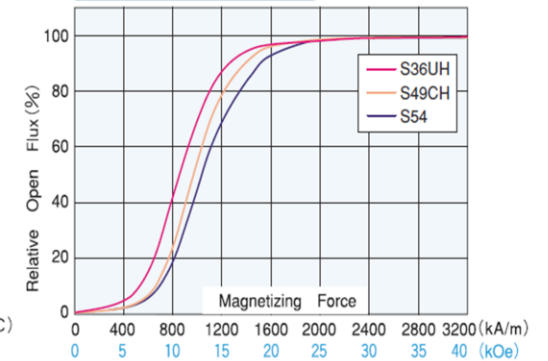
*1 C//: The measured value in the axial direction that allows easy magnetization

*2 C⊥: The measured value in the direction perpendicular to the axial direction that allows easy magnetization

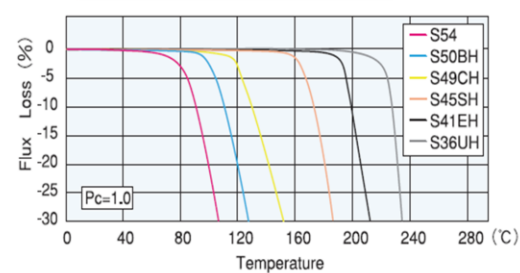
Range of Magnetic Properties



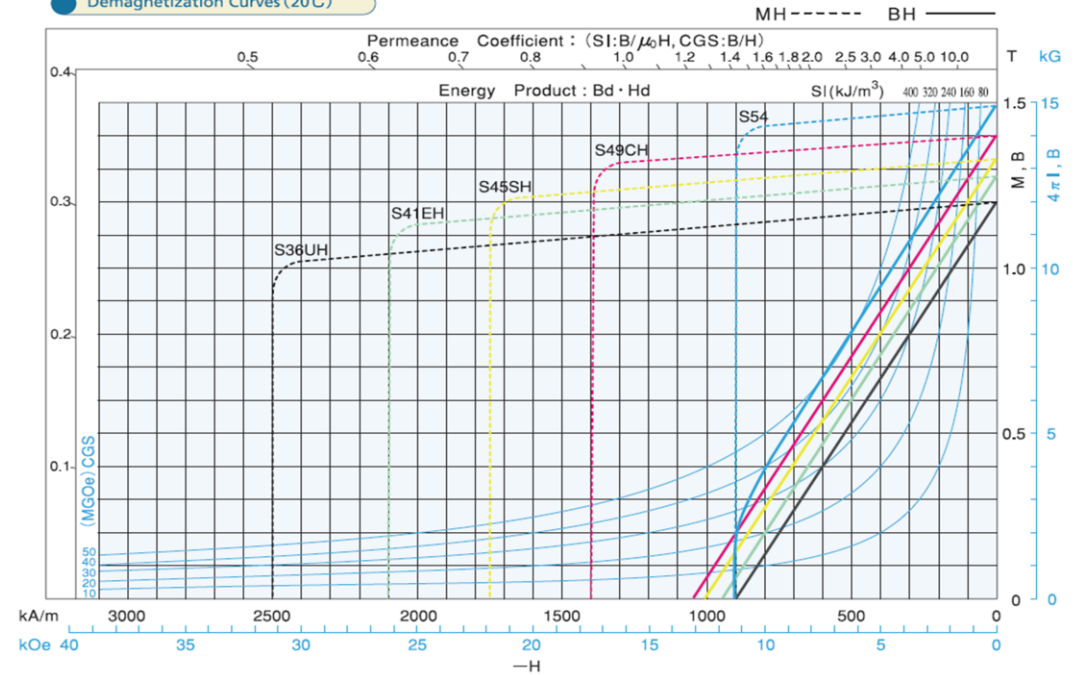
Magnetization Characteristic



Thermal Demagnetization Characteristic



Demagnetization Curves (20°C)



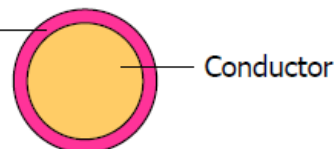
APPENDIX H

Table H.1 : Properties of the copper used in the field and stator windings.

BEMTERM

Insulation Type

Base Coat : Theic Polyesterimide
Over Coat : -
Bonding Layer : -
Lubricant : Available



Standard

IEC 60317 – 8
DIN EN 60317 – 8
NEMA MW 30 C, MW 74 C

Layer and Size Range

Grade 1 $0,030 \leq \varnothing \leq 5,000$ mm
Grade 2 $0,030 \leq \varnothing \leq 5,000$ mm

UL Approval

BEMTERM
UL file # OBMW2.E214939

Application Fields

- * Motors
- * Transformers (especially dry type)
- * Automotive Components
- * Alternators

Properties

- * Thermal index of 180 °C
- * High thermal resistance up to 200 °C

Technical Characteristics

Thermal

Thermal Index	°C	180
Heat Shock	°C	> 200
Cut-through Temperature	°C	> 320

Electrical

Breakdown Voltage	V	$\geq 2 \times$ IEC Value
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Chemical

Resistance to Solvent	H	5 H
Resistance to Refrigerants		Very Good
Resistance to Transformer Oil		Good

CV

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- **Operating Systems**
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- **Office Applications**
MS Office, MathType, Open Office
- **Field Programs**
MatLAB, Proteus (ARES, ISIS), Maxwell, PSIM, AutoCAD

CG & SOFTWARE

- **Microcontroller Hardware-Software**
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PUBLICATIONS/ PRESENTATIONS	1. Tayfun Gündoğdu, Güven Kömürgöz, "Design of Permanent Magnet Machines with Different Rotor Type", ICEMPE 2010, Paris/France. 2. Tayfun Gündoğdu, Güven Kömürgöz, "Yüzey Mıknatıslı Doğru Akım Motor Tasarımı", Elektrik ve Elektronik Mühendisliği Konferansı (ELECO'10), 2-5 Aralık, Bursa/TÜRKİYE (in Turkish). 3. Tayfun Gündoğdu, Güven Kömürgöz, "The Design and Comparison of Salient Pole and Permanent Magnet Synchronous Machines", 7th International Conference on Electrical and Electronics Engineering, (ELECO'11) 1-4 Dec., Bursa, TURKEY. 4. Tayfun Gündoğdu and Güven Kömürgöz, "Technological and Economical Analysis of Salient Pole and Permanent Magnet Synchronous Machines Designed for Wind Turbines", Journal of Magnetism and Magnetic Materials. Vol. 324, Is. 17, pp. 2679-2686, Aug. 2012. 5. Tayfun Gündoğdu and Güven Kömürgöz, "Implementation of Fractional Slot Concentrated Winding Technique in Large Salient-Pole Synchronous Generators", IEEE Symposium on Power Electronics & Machines for Wind Application (IEEE-PEMWA'12), Denver, USA, Jul. 16-18, 2012. 6. Güven Kömürgöz and Tayfun Gündoğdu, "Comparison of Salient Pole and Permanent Magnet Synchronous Machines Designed for Wind Turbines" IEEE Symposium on Power Electronics & Machines for Wind Application (IEEE-PEMWA'12), Denver, USA, Jul. 16-18, 2012.