# Modeling and Experimental Analysis for Modernization of 100-t EAF

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***Abstract*—This paper presents an experimental investigation and modeling solutions of an electric arc furnace (EAF) with 100-t capacity used for steel melting in order to evaluate the best option for improvement. Experimental results show that EAFs represent a substantial source of electric disturbances such as voltage fluctuations, flicker, harmonics, and imbalance between phases. Improvement of the energetic performances of an EAF imposes a careful technical and economical analysis. The static voltampere reactive compensator solution is the best one for compensating the reactive energy and increasing the power factor but has the highest costs. Also, we evaluate existing processes' equipment performance, the point of improvement opportunities for the best operating efficiency. Substantial reductions in the energy consumption and in the defects of mechanical nature are obtained by the proposed automation solution of the auxiliary installations.**

***Index Terms*—Electric arc furnace (EAF), flicker, harmonic analysis, harmonic filtering, improvement, reactive compensator.**

## I. Introduction

THE ELECTRIC arc furnace (EAF) has been studied for many years, but it is still difficult to complete a representation of such a load and its impact on the power system.

Due to the arc's dynamic behavior during the melting process, an EAF is a major source of perturbations on a high-voltage network with a low short-circuit capacity. The perturbations are random in nature and encompass a frequency range from dc to few hundreds of hertz.

A large percentage of the world production is provided by large-capacity EAFs. These are placed among the biggest polluters of air, soil, water, and electric supply grids. Also, the energy consumption is significant. In order to keep up with the competitiveness of this industry, it is necessary to consider the cost reduction by means of upgrading the supply installations, auxiliary systems, and automation systems. At the same time, the environmental regulations need to be strictly fulfilled.

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Due to the fact that, during operation, the EAF presents a large variation of input power and the load phases are unequal, the asymmetric operation regime appears. This leads to distortion of current and voltage waveforms, a large variation of the reactive energy. This also leads to the appearance of high-order harmonics in current and voltage [1] and to the flicker effect [2]–[4].

Fluctuations in the currents drawn by EAFs may be large enough to cause voltage fluctuations in the electric distribution system, causing lamp flicker. Such voltage fluctuation may also affect sensitive electronic equipment such as television sets and computers. Such voltage fluctuations must be kept below the "irritation threshold" to minimize the effects [4].

Flicker at a certain point of common coupling (PCC) on the electricity transmission system is usually caused by more than one flicker source. Determining the main sources of the flicker and finding out how much each source contributes to the flicker at PCC is an important issue in order to apply appropriate flicker mitigation techniques to these flicker sources [5]–[8].

Problems related to flicker, reactive power, and harmonics, as well as to compensator solutions, have been widely discussed and studied in the literature. Traditionally, rotating synchronous compensator and fixed or mechanically switched capacitors or inductors have been used as reactive power compensators [9]. In recent years, static voltampere reactive compensators (SVCs) and active compensators have been developed [10], [11]. They can be considered consisting of thyristor-controlled reactors and thyristor-switched capacitors [7], [9].

Since stochastic changes occur in the supply voltages due to fluctuations in the arc's length, uncharacteristic harmonics around each characteristic harmonic are also produced with relatively low magnitudes. Uncharacteristic harmonics are concentrated in the frequency range from 0.1 to 30 Hz [12]. The amount of harmonic generation is dependent on the stage in the melting process [13]–[16].

In this paper, the main electric parameters for an EAF with a capacity of 100 t per heat and for the steel's secondary treatment installation, the Mannesmann type, are analyzed in order to propose the modernization solutions on the electric and automation side. These are considered the auxiliary installations that serve the furnace: exhausting, electrodes' control, cooling of the waste gas and furnace roof, water cooling towers, and pumping systems.

The steel factory presented here is located at the western side of Romania, and the EAF is 18 years from the initial installation.

# Modeling and Performance of Novel Scheme Dual Winding Cage Rotor Variable Speed Induction Generator with dc Link Power Delivery

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***Abstract*—In an effort to reduce the initial cost of a cage-rotor (robust) variable speed induction generator with full (100%) power PWM inverter, for a dc link local power bus, a novel dual stator winding configuration with a 50% rating PWM inverter and a capacitor and 50% diode rectifier (for additional active power delivery at high speeds capable of soft-starting and low speed operation) is proposal in this paper. Machine circuit modeling with performance assessment for steady state and a circuit model for system feed forward controlled dynamics are proposed and backed up by numerical power and efficiency versus speed results. Preliminary experiments on a purposely built prototype already validate the essentials.**

## I. Introduction

Induction generators have been employed to operate as wind turbine generators and small hydroelectric generators coupled to the grid or in isolated power systems [1], due to the practical advantages related to low maintenance cost, better transient performance, ability to operate without dc power supply for field excitation, good overload protection ability and brushless construction. With the development of the packaged high speed gas turbine and high speed diesel engine, it becomes increasingly questionable that the prime mover and the generator are connected by a gear reducer. On the contrary, a direct mechanical coupling between the prime mover and the generator has many advantages, such as low noise, high efficiency, and high power density. Optimal design of induction machine for low speed was developed [2].

For traditional induction generator systems [3], the major drawbacks are related to the difficulty of excitation (reactive) power regulation and the poor output voltage performance under the variations of load and speed, which limit their widespread applications. Grid connected induction generator with small parallel power converter [4] which control the synchronization process or with a series full power converter [5] that allow also energy storage in the dc battery are operate at fixed frequency that means almost constant shaft speed. A full power converter with bidirectional power flow [6] allows wide speed variation but the power converter cost is still to large for many applications. The wound induction machine allow to control the output power using low cost converter by controlling only the power transferred trough the rotor [7] or by using a two half controlled converter [8]. A configuration with two wound rotor induction machines could be used to avoid the slip ring and brushes [9], but especially in low speed applications the weight and cost of two machines is too large.

The double stator windings machine introduced by T.F. Barton since 1927 and developed by Ph. L. Alger [10], consists in two similar but separate three-phase stator wound windings with the same number of poles. Both stators are fed with the same frequency and the rotor is a standard squirrel cage. Dual stator winding induction generator with a converter connected to the control winding is used to supplies ac loads with reduced harmonic distortion [11]-[15] or d.c. loads by adding a diode rectifier on the load side [16]-[19]. The induction generator with split stator winding where only the control winding is connected to a power converter could not cover a large speed range without to oversize the induction generators. The low speed induction machines, usually, have a large magnetization current and if the power converter is placed in the load side and run as a active rectifier with a capacitor battery on the control side then the rated power of the active rectifier are not much larger than the power of the control converter and allows a wide speed range [20], but the generator efficiency is smaller in comparison with a single stator winding induction generator with the same power, speed and size.

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# Classical DC Excited Synchronous Generator for High Power Direct Driven Wind Turbine: Optimal Design and FEM Validation

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## Keywords

«Wind energy», «DC excited synchronous generator», «FEM analysis», «Optimal design», «Direct driven wind turbine».

## Abstract

The study considers a 7.6 MW, 180 poles, excited synchronous generator, for direct-drive wind turbine units. The paper introduces an optimal design and finite element verifications and it compares these results with literature. Design with MATLAB, 2D FEM analysis and the optimal design represent the core of the paper.

## Introduction

The wind energy conversion is growing faster in terms of numbers of installed units and also in power capability per unit [1, 2]. Comparisons of direct driven and gearbox wind turbine with dc excited synchronous generator, dcSG, permanent magnet synchronous generator, PMSG, and double fed induction generator, DFIG are presented in [3] while for large power direct drive only the PMSG [4] and DFIG [5-6] were studied in detail.

The scope of this paper is to reconsider the dc SG for large direct driven wind turbines in the context of PMs crises. The excitation rated power necessary to transfer in the rotor is small for all speed range and it could be contactless transferred by using a high frequency rotating transformer and rotating rectifier placed in the rotor [7].

The target power of the dcSG presented in this paper is 7.6 MW at 11.7 rpm similar to the largest direct drive generator from Enercon E126. The rated voltage is also 400V as in E126. The paper presents the benefits and limits of analytical design [8-9] in comparison with finite element method for an unusual synchronous generator.

## Optimal Design

A modified Hooke Jeeves algorithm is used for optimal design of the dc excited synchronous generator. The optimization variable vector contains 11 variables: $J_l$–linear electric load, $B_{ag}$ – air-gap flux density, $\lambda_c$ –ratio between core length and pole pitch, $J_s$ – stator current density, $J_e$ – excitation current density, $B_{st}$- stator teeth flux density, $B_{sy}$ – stator back iron flux density, $B_{rt}$ – excitation pole flux density, $B_{ry}$ rotor back iron flux density, $y_1$ – stator relative coil span, $\alpha_p$ – rotor pole relative width (ratio between pole width and pole pitch). The probability to reach the global optimum using Hooke Jeeves (HJ) algorithm could be increased by starting the algorithm several times from different points of the optimization variable space. The number of parallel current paths is equal to the number of poles and thus the coil current is small. Consequently, round wire with closed slots is used in the stator. The low voltage level allows to use thinner insulation and the minimum value of the slot width

# Experimental study and comparative analysis of transients of induction motor with soft starter startup

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***Abstract* — This paper investigates the influence of the parameters of the machine and of the soft starter on the dynamics of the induction machine start. In order to evaluate the effects of this variation we have used a design of experiments (DOE). The situations may reproduce actual situations occurred in practice, for example the variation of initial voltage $U_i$, modification of the start time and load value.**

**In the present paper we have investigated the relation between the inrush current, voltage dip at the startup of one industrial soft starter. Using an already predefined fire angle characteristic the influence of the initial voltage was also evaluated.**

***Index Terms*—AC Motor drives, Converters, Power semiconductor switches, Speed control.**

## I. INTRODUCTION

Electrical drives based on induction motors are the most widely used electromechanical systems in modern industry. Due to their reliability, ruggedness, simple mechanical structure, easy maintenance and relatively low cost, induction motors are attractive for use in a new generation of electrical transportation systems, such as cars, buses and trains [1], [2].

From the variety of electric energy consumers in industry one of the largest is without any doubt the induction machine operating as motor. Besides the classical destination of the induction machine as motor this machine is more and more used in the latest period as generator in the conversion chain of wind or micro-hydro-energy into electricity [3], [4], [5].

Variable voltage operation of a squirrel cage induction machine at part load is receiving considerable attention as an energy conservation measure. In particular, the power factor controller has created an interest in energy-saving schemes for all types of electric motors [6]. The switching of three-phase induction machine under different operation conditions is one of the processes frequently performed through speed control, soft starting , energy-saving and in renewable energy applications. It is well-known that the transient behavior associated with frequent switching of induction machines is characterized by high current peaks and pulsating torques. Such performance is most undesirable for both electrical supply and mechanical gearing systems [7].

Direct online induction machine starts have many disadvantages. Torque pulsations are often large and modify from positive to negative values. These torque transients in a motor shaft are transmitted to the load, resulting in mechanical wear in the motor bearings and load couplings. Therefore, properly controlling the starting currents and torques of induction machines is of great importance in many instances. Additionally, the resulting starting currents are high, especially during the first few cycles of a starting transient. This high currents are endured by the motor and power system, causing the heating of the machines windings [8].

In recent years, a variety of power electronics equipment with voltage fed pulse width modulation inverters (VSI - PMW) used widely in industrial applications and power network systems have caused significant inherent problems, such as generation of reactive current and power, as well as higher harmonic distortion in the power sources. The selection of the best PWM technique for most applications is uncertain, which can lead to less than optimum results [9].

Soft starters using silicon-controlled rectifiers (SCRs) are now used extensively in the industry. This starting method essentially allows the control of the voltages applied to an induction motor and hence, control of its torque and the acceleration of a machine during its starting transient [8], [10].

Appearance of soft starters produced a qualitative raise in starting, stopping or braking matter of induction motors with squirrel cage. These equipments are useless at starting-up of induction motors with phase wound rotor. There are numerous producing companies that offer soft starters at low voltages (400 and 690 V) or medium voltages (3.3, 4.2, or 6 kV) [11]. Can be started-up even electric drive systems that have a load torque and an inertia moment of equivalent high values.

The basic way of finding out the inertia moment is through analytic calculation, based on the rotor drawing and materials. Modern design rules take full benefit of the powerful capabilities of computer-aided design (CAD) tools, and once the rotor is entirely defined geometrically and material wise, automatic calculation of the inertia moment for the rotating parts may be easily achieved. Based on the accurate measurements brought by the modern digital-data-acquisition tools, the moment of inertia can be obtained in different manner [12].

The soft starters of switch all three phases are controlled can use the starting-up or shutting-down by means of voltage, current or torque control [13]. At voltage control, is achieved a soft start-up, but it's not generated any current or torque reaction. The typical quantities for starting-up with voltage raise are the initial voltage $U_i$ and the starting-up ramp's duration $t_p$. The currents and voltages versus time variation in this case are presented in fig. 1a and b. By $I_{max}$ was noted the maximum current obtained during the start-up and by $I_R$ the load current [14], [15].

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# The Single Stator Dual Rotor PMSM for HEV: Two Windings and 4 Leg Inverter Control

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*Abstract* — **This paper proposes a single stator dual rotor PMSM for HEV drive-system with two distinct stator windings in Δ connection, four leg inverter and two capacitors connected in series, with Field Oriented Control new solution. The four leg inverter that drives the two rotors should result in additional reliability and compactness through at the cost of addition kVA rating. The A and B phases of both machines are connected to dedicated legs whereas C phase of both machines is connected to the neutral point of the two-split capacitors. The standard PWM technique in three-phase voltage source inverters is not directly applicable because only two phases may be modulated. So, a dedicated PWM strategy that reduces the capacitor middle point voltage pulsations is introduced and "tested" through extensive digital results.**

*Keywords* — **Axial PMSM, Four leg inverter, Split capacitors inverter.**

## I. INTRODUCTION

In last years, some research efforts have been directed to develop a new family of power converters with reduced costs and losses. A solution is the three-phase voltage-source inverter (VSI) with only two inverter legs. In comparison with the usual three-phase VSI with three inverter legs, the main features of this converter are: reduced switch and freewheeling diode count, reduced price, reduced number of drive circuits and reduction of losses. Despite these advantages, the main shortcomings of this topology are: decreased voltage gain and thereby increased current rating for the devices at the same output power, increased stress in both power devices and electric machine and large variations of the voltage across the two DC-link capacitors [1].

Traditional AC drives are based on a three-phase inverter that is used to feed an electric machine; thus, a total of six switches is required. Reducing the number of active switches is desirable in applications where low cost, improved reliability and less conduction loss are of importance. Due to its many advantages, a two-phase topology using a split DC-link capacitor requiring only four switches was introduced in [2]-[4].

The proposed new dual AC-drive system uses two four-switch inverters connected back to back which share a single split DC-link capacitor. The inverters are used to feed a single stator dual rotor PMSM that operates at different frequencies as motor/or generator. We use "optimally" two distinct stator windings (to avoid magnetic coupling and reduce copper stator losses) but only a four leg inverter.

Fig. 1 shows schematically the proposed drive system.

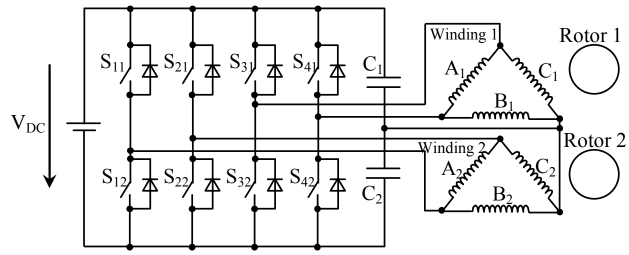


Fig. 1 Proposed single stator dual rotor PMSM drive-system with two distinct stator windings and four leg inverter

Typically, [4]-[8], the machine phases are Y connected. Hereby we propose Δ connection of the two windings to maintain the phase voltage at same level as in 3 leg inverters. This means the wire diameter is smaller, the winding may be build easier and, for an existing machine, no rewinding is needed.

However, the 3, 6, 9, 12 order harmonics can travel freely in the Δ winding and need an assessment of their influence.

The design, construction and control of drive system with a 3 leg inverter were presented in [9]-[12].

## II. SYSTEM CONFIGURATION AND PRINCIPLE OF OPERATION

High torque density and high efficiency are two of the most desirable features for an electrical machine. Rare earth magnets, e.g. Neodymium Iron Boron (NdFeB), were used in our system, to keep the efficiency high and achieve the high air gap flux density and high torque density [13], [14], despite of PM rather high price.

The stator assembly is with the two three-phase windings placed in the open slots. In double layer, non-overlap, slotted iron-cored, windings two coils are sharing a slot (two coil layers per slot), which means that all teeth are wound. Consequently these windings are sometimes called tooth windings. The rotor structures are exactly the same in both machines, which are composed of surface mounted axially magnets and rotor discs.

This topology is proposed for a hybrid vehicle where a machine is coupled to the thermal engine and the other one to the vehicle wheels.

Now that the operation is independent in the two twin motor/generator, the number of stator slots and rotor poles may be chosen freely for the twin machines.

Due to the circuit configuration, the maximum obtainable peak value of the line-to-line voltage equals $V_{DC}/2$.

For the analysis, the inverter is considered to be built by ideal switches. The output voltages are defined by the gating signals of the two leg switches and by the two

# Design and Control of a Single Stator Dual PM Rotors Axial Synchronous Machine for Hybrid Electric Vehicles

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## Keywords

«Hybrid electric vehicle», «Control of drive», «Design», «Permanent magnet motor».

## Abstract

In this paper is presenting the preliminary designing and control of a synchronous machine with axial airgap single stator dual-rotor with permanent surface magnets and different pole pairs number, destined for hybrid electric vehicles (HEV) applications.
For machine's designing was used the equivalent magnetic circuits method that takes into account the saturation and dispersion of the magnetic field.
The control model is developed for a single inverter that produces three phase output voltage with two frequencies components; the torque current for each rotor is controlled through the stator current that passes the two serial windings.
The machine, coupled with the thermal engine (ICE), can operate as starter for short time at start-up and as generator, when the rotational speed is established by the thermal engine's regulator.
The other machine can operate as motor in wide speed range (both inferior and superior to the generator's), but also in generator regime with power recovery at braking.

## Introduction

The concept of the electric vehicle (EV) was conceived in the middle of the 19 Century. After the introduction of the internal combustion engine (ICE), EVs remained in existence side by side with the ICE for several years. The energy density of gasoline is for more than what the electrical battery could offer [1].
The early air quality concerns in the 1960's and the energy crisis in the 1970's have brought EV's back to the street again. Hence, the problem associated with ICE automobiles is threefold: environmental, economical and political. These concerns have forced governments all over the world to consider alternative vehicle concepts. EV's and hybrid-electric vehicles (HEV's) offer the most promising solutions to reduce vehicular emissions [1]-[3].
Axial Flux Permanent Magnet (AFPM) Machines first appeared in the technical literature in mid 70's. Soon their field of application spread widely. Today, among the most prominent appliances are fans, elevators, ships, vehicles and airplane propulsion [4]-[8].
Beside the enumerated applications, the synchronous machine with permanent magnets and axial air-gap can also be used in the field of hybrid vehicles.
Basically, a hybrid propulsion system includes two electric machines: one is used to while drive; while the other is mainly used for battery charge. Although these machines play different roles, their operating cycles are more or less linked. Moreover, their locations within the power train represent a

# Dual rotor single- stator axial air gap PMSM motor/generator drive for HEVs: a review of comprehensive modeling and performance characterization

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Abstract - **In an effort to simplify the planetary-geared e-CVT for the parallel HEV or the series HEV we hereby propose-in a synthesis of these authors quite a few previous recent IEEExplore papers on the subject- to replace the basically two electric machines and their two power converters by a single, axial-air-gap, electric machine central stator, fed from a single PWM converter with dual frequency voltage output and two independent PM rotors capable to deliver independently torque by adequate vector control. The paper presents preliminary design with Matlab, optimal design via Hooke Jeeves method, sample quasi-2D and 3-D FEM results and dual vector control of a synchronous machine with axial air-gap single stator dual-rotor with permanent surface magnets and different pole pair's number, destined for hybrid electric vehicles (HEV) applications. For machine's designing the equivalent 3D magnetic circuits method, that takes into account the saturation and the magnetic field fringing, was used. A control model is developed for a single inverter that produces three phase output voltages with two frequency components. The modeling and performance characterization, and dual vector control show promising results, but experiments, which are now in preparation, are needed to prove the practicality of the proposed system.**

## I. INTRODUCTION

Crude oil price are expected to rise in the long term, and emissions from gasoline-driven automobiles are one of the main causes of global warming and environmental pollution. Modern hybrid and electric vehicle technology is one of the practical solutions to alleviate these environmental problems. Currently, almost all the automotive producing companies have developped at least one hybrid model [1]-[3].

Modern hybrid and electric vehicles use high performance motor drives. Recently, axial flux permanent magnet (AFPM) machines, which have high torque density, excellent efficiency, and reliability feature, are popular for various applications such as electric ship, hybrid and electric vehicle, and airplane propulsion due to their compact construction and high power density. The fractional slot, concentrated winding has shortened end windings compared with those of a distributed winding, resulting in lower power losses and shorter axial frame lengths, but the magneto motive force (MMF) has in general numerous harmonics. Soft magnetic composites (SMC) are proposed for stator core for its simple fabrication compared to laminated steel cores, which normally cannot be easily made by stampings; however, the permeability of SMC is low compared to that of the laminated steel. Segmented cores have been proposed for this kind of machines [4],[5].

Basically, a hybrid propulsion system includes two electric machines: one is used for wheel drive; while the other is mainly used for battery charge. Although these machines play different roles, their operating cycles are more or less linked. Moreover, their locations within the power train represent a drawback from the point of view of volume reduction. Therefore, the integration of both machines into an electromechanical set, in an attempt to improve the compactness and the cost-effectiveness, is currently considered a challenging technology [6]. Dual-rotor machines with toroidally (Fig. 1a) and radially (Fig.1b) wound stators have been reported recently in [7].

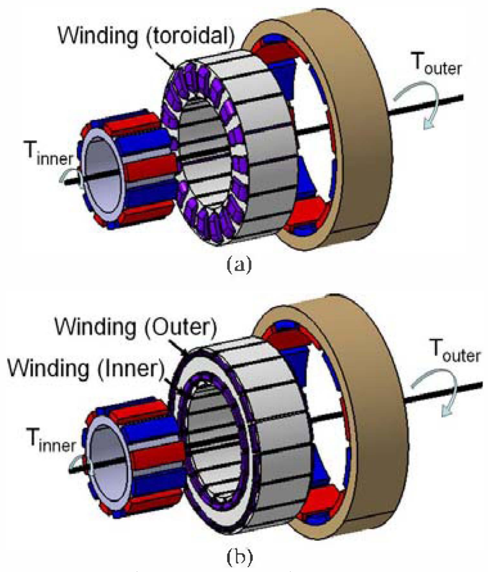


Fig. 1. Exploded view of (a) toroidally and (b) radially wound dual-rotor machines with 12 rotor poles and 18 stator slots.

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# Modeling and Experimental Investigations of a Reactive Homo-Heteropolar Brushless Synchronous Machine

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**Abstract - In this work is presenting a reactive homo-heteropolar brushless synchronous machine (RHHBSM), with stator excitation destined to operate as low power generator in hydroelectric, or wind power stations, or as servomotor with reduced inertia. We proposed in this paper a modeling and a simulation method by electric-magnetic coupled network, based on the permeance network, 3D analysis with a specialized software and the machine's orthogonal model.**

**One prototype machine has been studied. Within this paper, we make a comparison between the results obtained by modeling with the magnetic equivalent circuits, finite element method and experimental results.**

## I. INTRODUCTION

One of the main disadvantages of the classic synchronous machines is the armature's excitation winding which determines a great rotor weight and inertia and involves the sliding contacts' existence (brushes and slips rings). Reference [1] presented a new form of heteropolar linear synchronous machine that is capable of providing both thrust and lifting force at relatively high efficiencies and power factor. In [2] is presented a rotary reactive homopolar synchronous machine with stator excitation which removes the disadvantages of the classic synchronous machines.

Conception constraints on electro-technical devices require numerical simulations to be as close as possible to its actual operating conditions. Then, it is necessary to have coupled physical models of devices, especially, for electrical, magnetic and mechanical coupled models which allow the simulation of loaded rotating machines [3].

Finite elements method (F.E.M.) allows such coupling for 2D plan modeling devices. Nevertheless, it requires a lot of calculation time. Its use for three dimensional typical machine has never been done until nowadays and calculation time will be even longer [4].

In order to obtain the best results in designing of the special electric machines, it should be used both the classic methods and the numerical calculation methods. The calculation should be based on a mathematic model as accurate possible. Based on this model are determined by simulation the characteristics of the machine in non-saturated and saturated regime [2], [5].

The designing particularities of these types of generators are linked to the axial character of the magnetic field distribution. The field calculation in the machine can be achieved by the finite elements method [6], or by field tubes method [2], [5], [7].

Taking into consideration the axial distribution of the machine field, it is necessary a three-dimensional modeling of the machine field. For this three-dimensional model is required a specialized software that needs a performance computer, and the calculations time could be high. The field tubes method brings acceptable simplifications, considering the magnetic saturation of the ferromagnetic core and the types of electric windings. We account for magnetic part with a permeance network. These permeances are indentified by mathematical calculation. The hysteresis effects are taken into account.

Experimental determinations are performed on a prototype already built with nominal power of 2.5 kVA.

## II. THE CONSTRUCTIVE ELEMENTS

The RHHBSM which we'll analyze further is a rotary machine. In order to understand its constructive elements, in fig.1 is presenting a longitudinal section. The excitation coil has a ring shape and is placed in the windows of the E-shaped laminations stack, and, at passing of the rotor poles, the field is closing, having by this a rectangular variation form. When the rotor pole is not under the laminations stack, the field is practically null.

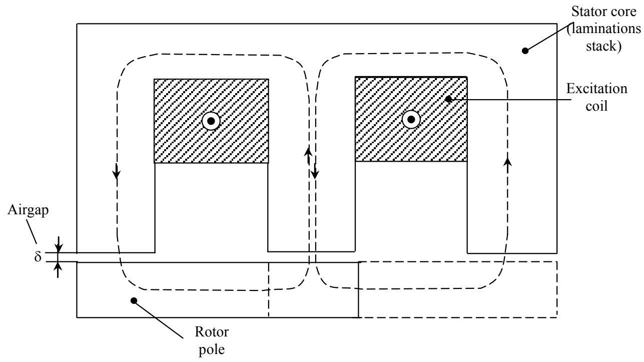


Fig. 1. Longitudinal magnetic circuit section.

# Design and FEM Validation for an Axial Single Stator Dual Rotor PMSM

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***Abstract*-A novel synchronous machine-the single stator dual PM rotor brushless, axial-flux, concentrated double layer fractional tooth winding, single inverter with dual frequency PWM independent control for two shafts – has been proven in previous papers of these authors to be able to improve the machine efficiency and boost the torque density. This paper will present the key design equations and design procedure of the Single Stator Dual Rotor PMSM by the equivalent magnetic circuit method , analyze skewed PM angle effects on machine performance and give design guidelines to achieve specific design objectives. A quasi-3D finite-element analysis with specialized software is given to prove the effectiveness of the design equations and find the main characteristics of the machine.**

## I. Introduction

The axial flux permanent magnet (AFPM) machine, also called the disc-type machine, is an attractive alternative due to its pancake shape, compact construction and high power density. AFPM motors are particularly suitable for electrical vehicles, pumps, fans, valve control, centrifuges, machine tools, robots etc [1], [2].

Axial flux machines appeared in the technical literature in the early '70s and trading of axial flux induction motors started few years later [3]-[6]. Nowadays, direct drive applications that require actuators or generators capable of operating at low speeds with large torques have revived the attention towards Axial Flux Machines, especially for the PM type, as they are capable of larger torque density and efficiency [3], [7]-[11].

However, AFPM Synchronous Machines become advantageous whenever a number of design prescriptions are fulfilled. Most notably, it is widely accepted that the number of pole pairs must be conveniently high [3], [12].

Fractional slot windings can be often realized in concentrated layouts: this happens when windings overhangs are not overlapped and the coils are wound individually around the stator teeth. Fractional Slot Concentrated Windings offer remarkable advantages both on the end user and to the manufacturer. In fact, they allow the physical separation of the phases and of the magnetic circuits of the phases, thus reducing the risk of phase-to-phase faults and minimizing the mutual inductance among the phases [3], [13].

The features of Single Stator Dual Rotor PMSM are summarized as the following: greatly shortened end windings, high ratio of diameter to length, high efficiency, high torque density and low material costs [14], [15].

## II. Design Equations

This paper will derive the main design equation and a design procedure for these machines, but provided with two rotors. In addition, quasi 3D finite-element analysis is employed to prove the effectiveness of the design equations and the main machine characteristics.

In fig. 1 a drawing of longitudinal section is shown. The single stator dual PM rotor axial synchronous machine has in centre the stator assembly (1) with the two three-phase windings (2) placed in open slots, fixed rigid in the casing (3), provided with two side covers (4), (5) in which the two ball bearings supports (6), (7), one radial and one axial, are introduced. The ball bearings allow the two shafts (8), (9) to rotate independently, each shaft having in the side towards the stator a disk of solid steel on which the permanent magnet poles are placed in circular and symmetric manner . The other end of the shaft is inserted into a half-coupling which is connected to the thermal engine (10), respectively, to the gears towards the drive wheels (11).

Many unknown parameters are involved in the design of the Single Stator Dual Rotor PMSM. As a result, it is necessary to assign some description to these parameters. They will be further explored in the design equations. Table I gives a list of the parameters used in the design approach.

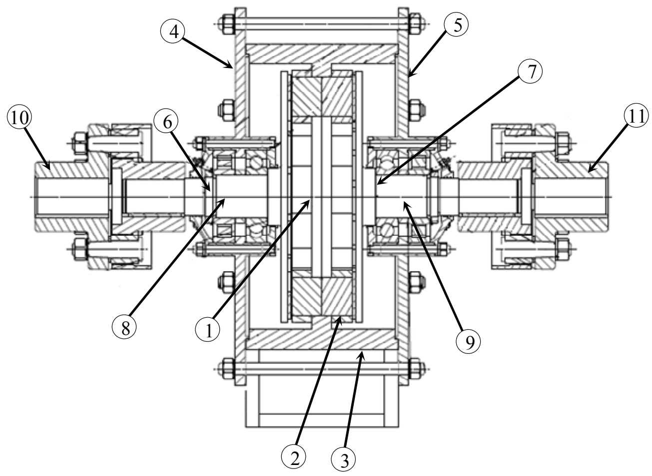


Fig.1. Longitudinal section through the dual PM rotors machine.

# Design, Control and 2D-FEM Validation for an Double Stator Winding Induction Generator

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*Abstract*—**This paper will present the key design equations and control design model of the Double Stator Winding Induction Generator (DSWIG) to achieve wide-speed-range operation with reduced capacity of the static power controller for low power wind or hydro applications. The proposed induction generator consists of a standard squirrel-cage rotor and a stator with two separate windings wound for a similar number of poles. Moreover, the system control strategy using the stator flux orientation is consequently proposed. A 2D finite-element analysis with specialized software is given to prove the effectiveness of the design equations and find the main characteristics of the machine.**

***Keywords—control design; induction generators; double stator winding; capacitor; FEM analysis; low speed; wind energy; hydro energy***

## I. INTRODUCTION

The dual-stator-winding squirrel-cage induction machine is the most recent innovation in the family of induction machinery. There are broadly two designs: the first type has two stator windings wound for the same pole numbers with similar or dissimilar phase numbers, and the second design has two stator windings with dissimilar pole numbers with the same or unequal phase numbers [1], [2]. There is also the brushless doubly fed induction machine that has two stator windings wound for dissimilar pole numbers and a specially designed nested loop rotor structure that couples the two airgap flux linkages derived from the two stator windings. The synchronous mode of operation of this the machine appears to be the most profitable, particularly for converter-based drive control [3]-[5].

The research in this domain is apparently reorienting, from permanent magnet synchronous generators (PMSG) towards the three-phase/multi-phase/single-phase multi-winding stator, squirrel cage rotor induction generators, chiefly dual-stator generators, to overcome the drawbacks of named synchronous generators, namely [6]-[9]:

- difficulties to obtain magnetic induction sinusoidal distribution along the machine air gap and, consequently, the appearance of voltage and current distortions, that determine increase losses and efficiency decrease;
- construction difficulties and low safety level insertion technology of PMSG;
- cogging torque, that complicates the start up of generator sets (e.g. in the case of unregulated blades wind generators);
- demagnetization risk due to thermal phenomenon determined by Foucault currents in the poles material;
- high cost of a large number of poles of low rated rotation speed generators;
- limited short-circuit safety-braking torque;
- difficulties of excitation control, and thus lack of optimization possibility at variable load currents, opposite to optimization opportunities of the induction machines.

Induction generators have been employed to operate as wind turbine generators and small hydroelectric generators in isolated power systems [10], [11], due to the practical advantages related to low maintenance cost, better transient performance, ability to operate without dc power supply for field excitation, and brushless construction. In a split-wound machine, the stator winding consists of two similar but separate three-phase windings wound for the same number of poles. Both stators are fed with the same frequency and the rotor is a standard squirrel cage. The two stator windings are mutually coupled and small unbalances in the supplied voltages generate circulating currents. Furthermore, because of the low impedance to harmonic currents there is a high level of circulating currents when a no sinusoidal voltage source supply is used, adding losses and demanding larger semiconductor device ratings [6]-[9], [12].

The paper is organized as follows: Section 2: proposed DSWIG phase coordinate model and design results, Section3: control model and dynamic simulations, Section 4: 2D-FEM validation parameters and characteristics, Section 5: conclusions.

## II. COORDINATE MODEL AND DESIGN RESULTS

Figure 1 present the proposed power generation system which have an active rectifier in the main winding and direct connected capacitances in excitation winding. In the proposed scheme the power electronics (active rectifier) is placed in the main windings while in the equivalent variable capacitor, [13] it is used on the excitation winding. The main advantage of active rectifier is the induction generator voltage boosting at low speed while with equivalent variable capacitor this is not possible.

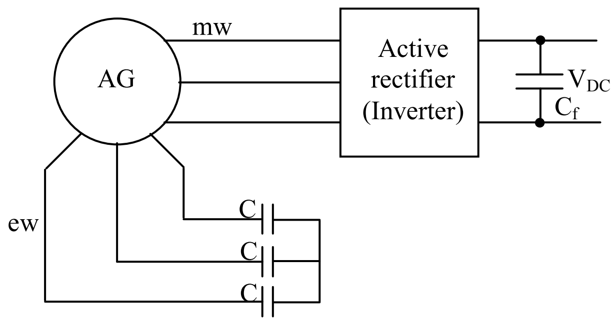


Fig.1. Dual stator winding induction generator with a rectifier (proposed scheme).