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PM synchronous machine PMSM Performance Improvement

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Abstract- Due to the importance of PM synchronous machine in many categories like in industrial, mechatronics, automotive, energy storage flywheel, centrifugal compressor, vacuum pump and robotic applications moreover in smart power grid applications, this paper is presented. It reviews the improvement of permanent magnet synchronous machines performance researches. This is done depending on many researchers' papers as samples for many aspects like: modelling, control, optimization and design to present a satisfied literature review

Keywords: Permanent Magnet, Synchronous machine, Control, High Speed, Design, Optimization, and Review.

1. INTRODUCTION

PERMANENT Magnet Synchronous Machines (PMSMs) are widely applied in many applications due to their high efficiency, low inertia and high torque – to – volume ratio. PMSM have the following advantages over dc motors: Less audible noise, Longer life, Sparkless (no fire hazard), Higher speed, Higher power density and smaller size, and Better heat transfer. Also, PMSM have the following advantages over induction motors: Higher efficiency, Higher power factor, Higher power density for lower than 10 kW applications, resulting in smaller size, and Better heat transfer [1]. Introduction of the line – start PMSM in the 1950s provided a solution to starting problem. The rotor of line – start PMSM is made of permanent magnet embedded inside a squirrel – cage winding. Induction of current in the squirrel cage produces torque at zero or higher speeds the same way torque is generated in induction motors. Therefore, the line – start PMSM can develop torque at zero speed, and run as an induction motor, until the synchronous speed is reached. Once the rated speed is reached the rotor is synchronized with the power source, and no more current is induced in the squirrel cage. After this, the motor runs as a synchronous motor. However, the high cost of line start PMSM inhibited its wide spread usage. Eventually, a motor drive was used to convert dc power into ac power with any desired frequency, and to deliver the power to the motor in a controlled manner. This development allowed the PMSM to be used efficiently at any speed. The introduction of high performance motor drives has rendered the line start PMSM almost obsolete. Park's theory presented a transformation between variables in the stationary and the rotor reference frames which yields the two – axis equivalent circuit for a PMSM. From the rotor's point of view every variable has a magnitude and angle which is constant in steady state. This means that using equations and variables in the rotor reference frame makes the analysis and control of PMSM much easier. Essentially, Park introduced auxiliary variables in terms of which the machine equations become much simpler. Availability of this transformation led to a field referred to

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as "vector control." Vector control enables independent control over the magnitude and angle of current with respect to the rotor such that instantaneous control over torque is possible. Application of vector control to a PMSM allows for linear control over torque, as well as control over different performance criteria such as efficiency and power factor. Several trends, starting in the 1970s, created a demand for high performance variable speed motor drives [1-5].

2. SELECTED PREVIOUS WORK

PM motor drives have been a topic of interest for the last twenty five years. Different authors have carried out modeling, and simulation of such drives. In the past, AC synchronous machines were used mostly for generator applications. Their use as a motor was limited due to the difficulty of controlling the frequency of their supply voltages. The introduction of power electronics PWM inverters has allowed the motor drive to have complete control over the magnitude and frequency of machine phase to phase voltages. Another factor that helped the development of PM synchronous machines is the expansion of industrial production of permanent magnets. The first magnet type to be produced on an industrial scale was the Alnico in the early twentieth century. As a result, S. Evershed [6], [7] in 1920 made some important contributions to principles of PM torque production. At first, PM machines received severe criticism because of the large tolerance they have in terms of control parameters. Permanent magnet materials exhibit important nonlinearities and are sensitive to temperature and operating point. In 1946, W. Kober first mentioned using PM synchronous machines for alternator applications [8]. In 1951, R. M. Saunders and R. H. Weakley significantly contributed to their design considerations [9]. Most of these first approaches to PM machine design considered only Alnico type magnets. Rare earth magnets, which are significantly superior to the Alnico type, appeared in the 1970s. While at first very expensive, these materials have found an increasing interest in the last few years and are now commonly used in PM machines. PM synchronous machines present several advantages when compared to the other type machines. First, the PM machines present a much larger energy density and can therefore be of smaller size for a given power. They also have much lower rotor inertia, which is an important advantage for applications where a fast response is needed. Finally, the absence of brushes to supply the rotor circuit makes them much more mechanically robust. On the other hand, the price of PM materials is quite high and PM machines are not economically interesting above a certain power rating (about 20 kW). So other machines are consequently still used, typically for electrical energy production. In 1986 T. Sebastian, et al. [10] reviewed permanent magnet synchronous motor advancements and presented equivalent electric circuit models for such motors and compared computed parameters with measured parameters. Experimental results on laboratory motors were also given. In 1986 T.M. Jahns et al. [11] discussed that interior permanent magnet (IPM) synchronous motors possessed special features for adjustable speed operation which distinguished them from other classes of ac machines. They were robust high power density machines capable of operating at high motor and inverter efficiencies over wide speed ranges, including considerable range of constant power operation. The magnet cost was minimized by the low magnet weight requirements of the IPM design. The impact of the buried magnet configuration on the motor's electromagnetic characteristics was discussed. The rotor magnetic saliency preferentially increased the quadrature-axis inductance and introduced a reluctance torque term into the IPM motor's torque equation. The electrical excitation requirements for the IPM synchronous motor were also discussed. The control of the sinusoidal phase currents in magnitude and phase angle with respect to the rotor orientation provided a means for achieving smooth responsive torque control. A basic feed forward algorithm for executing this type of current vector torque control was discussed, including the implications of current regulator saturation at high speeds. The key results were illustrated using a combination of simulation and prototype IPM drive measurements. In 1988 Pillay and Krishnan, [12], presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. The PMSM is very similar to the wound rotor synchronous machine except that the PMSM that is used for servo applications tends not to have any damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence the d, q model of the PMSM can be derived from the well known model of the synchronous machine with the equations of the damper windings and field current dynamics removed. Equations of the PMSM are derived in rotor reference frame and the equivalent circuit is presented without dampers. The damper windings are not considered because the motor is designed to operate in a drive system with field-oriented control. Because of the non-sinusoidal variation of the mutual inductances between the stator and rotor in the BDCM, it is also shown in this paper that no particular advantage exists in transforming the abc equations of the BCDM to the d, q frame. As an extension of his previous work, Pillay, and Krishnan in 1989 [13] presented the permanent magnet synchronous motor (PMSM) which was one of several types of permanent magnet ac motor drives available in the drives industry. The motor had a sinusoidal flux distribution. The application of vector control as well as complete modeling, simulation, and analysis of the drive system were given. State space models of the motor and speed controller and real time models of the inverter switches and vector controller were included. The machine model was derived for the PMSM from the wound rotor synchronous motor. All the equations were derived in rotor reference frame and the equivalent circuit was presented without dampers. The damper windings were not considered because the motor was designed to operate in a drive system with field-oriented control. Performance differences due to the use of pulse width modulation (PWM) and hysteresis current controllers were examined. Particular attention was paid to the motor torque pulsations and speed response and experimental verification of the drive performance were given. S. Morimoto et al. in 1994 [14], in their paper aimed to improve efficiency in permanent magnet (PM) synchronous motor drives. The controllable electrical loss which consisted of the copper loss and the iron loss could be minimized by the optimal control of the armature current vector. The control algorithm of current vector minimizing the electrical loss was proposed and the optimal current vector could be decided according to the operating speed and the load conditions. The proposed control algorithm was applied to the experimental PM motor drive system, in which one digital signal processor was employed to execute the control algorithms, and several drive tests were carried out. The operating characteristics controlled by the loss minimization control algorithm were examined in detail by computer simulations and experimental results. The paper in 1997 by Wijenayake and Schmidt [15], described the development of a two-axis circuit model for permanent magnet synchronous motor (PMSM) by taking machine magnetic parameter variations and core loss into account. The circuit model was applied to both surface mounted magnet and interior permanent magnet rotor configurations. A method for on-line parameter identification scheme based on no-load parameters and saturation level, to improve the model, was discussed in detail. Test schemes to measure the equivalent circuit parameters, and to calculate saturation constants which govern the parameter variations were also presented. In 1997 Jang-Mok, and Seung-Ki, [16], proposed a novel flux-weakening scheme for an Interior Permanent Magnet Synchronous Motor (IPMSM). It was implemented based on the output of the synchronous PI current regulator reference voltage to PWM inverter. The on-set of flux weakening and the level of the flux were adjusted inherently by the outer voltage regulation loop to prevent the saturation of the current regulator. Attractive features of this flux weakening scheme included no dependency on the machine parameters, the guarantee of current regulation at any operating condition, and smooth and fast transition into and out of the flux weakening mode. Experimental results at various operating conditions including the case of detuned parameters were presented to verify the feasibility of the proposed control scheme. Bose, B. K., in 2001 [5], presented different types of synchronous motors and compared them to induction motors. The modeling of PM motor was derived from the model of salient pole synchronous motor. All the equations were derived in synchronously rotating reference frame and was presented in the matrix form. The equivalent circuit was presented with damper windings and the permanent magnet was represented as a constant current source. Some discussions on vector control using voltage fed inverter were given. C. Bowen et al. in 2001 [17], addressed the modeling and simulation of permanent magnet synchronous motor supplied from a six step continuous inverter based on state space method. The motor model was derived in the stationary reference frame and then in the rotor reference frame using Park transformation. The simulation results obtained showed that the method used for deciding initial conditions was very effective. In 2002 C. Mademlis et al. [18], presented an efficiency optimization method for vector-controlled interior permanent-magnet synchronous motor drive. Based on theoretical analysis, a loss minimization condition that determines the optimal q-axis component of the armature current was derived. Selected experimental results were presented to validate the effectiveness of the proposed control method. In 2004, X. Jian-Xin et al. [19] applied a modular control approach to a permanent-magnet synchronous motor (PMSM) speed control. Based on the functioning of the individual module, the modular approach enabled the powerfully intelligent and robust control modules to easily replace any existing module which did not perform well, meanwhile retaining other existing modules which were still effective. Property analysis was first conducted for the existing function modules in a conventional PMSM control system: proportional-integral (PI) speed control module, reference current-generating module, and PI current control module. Next, it was shown that the conventional PMSM controller was not able to reject the torque pulsation which was the main hurdle when PMSM was used as a high-performance servo. By virtue of the internal model, to nullify the torque pulsation it was imperative to incorporate an internal model in the feed-through path. This was achieved by replacing the reference current-generating module with an iterative learning control (ILC) module. The ILC module records the cyclic torque and reference current signals over one entire cycle, and then uses those signals to update the reference current for the next cycle. As a consequence, the torque pulsation could be reduced significantly. In order to estimate the torque ripples which might exceed certain bandwidth of a torque transducer, a novel torque estimation module using a gain-shaped sliding-mode observer was further developed to facilitate the implementation of torque learning control. The proposed control system was evaluated through real-time implementation and experimental results validated the effectiveness. Due to their reluctance torque production, the IPM motors are more suitable for traction applications which require constant power output at high speeds over a wide range [20]. With the rapid development of microprocessors (μC) and digital signal processors (DSP), vector control is becoming a common technique for PMSM drive systems, especially in low-cost applications such as home appliance and machine tools. The vector control (or called field-oriented control) of ac machines was introduced in the late 1960s by Blaschke, Hasse, and Leonhard in Germany. Following their pioneering work, this technique, allowing for the quick torque response of ac machines similar to that of dc machines, has achieved a high degree of maturity and become popular in a broad variety of applications. It is also widely applied in many areas where servo-like high performance plays a secondary role to reliability and energy savings. To achieve the field-oriented control of PMSM, knowledge of the rotor position is required. Usually the rotor position is measured by a shaft encoder, resolver, or Hall sensors [21-25]. The advantages of PM machines recently make them highly attractive candidates for “direct drive” applications, such as hybrid electrical vehicles (HEV) or electrical vehicles (EV) and washing machines. By this technology, the rotating working unit of a direct drive system, such as the basket or drum of a washing machine, is coupled to the motor shaft without transmission assembly, which may include clutches, belts, pulleys and/or gearboxes. The power is directly delivered to the working unit by the motor. The concept of direct drive enables the high dynamic response, increased efficiency, low acoustic noise, and long lifetime due to the elimination of the transmission components. Such direct drive systems normally require large shaft torque at standstill (i.e., zero speed) and low speeds as well as constant output power over wide speed range. In order to meet such requirements, the PM machines are designed to operate not only in the constant torque mode when their speed is below the base (or rated) speed but also in the constant power mode when above the base speed. In this way, the cost and size of overall drive system can be significantly reduced. The constant torque operation of PM motor can be easily achieved by conventional vector control. However, when the speed is above the base speed, the back-EMF of PM motor is larger than the line voltage and then the motor suffers from the difficulty to continuously produce torque due to voltage and current constraints. Thanks to the flux-weakening technology, the operating speed range can be extended by applying negative magnetizing current component to weaken the air-gap flux [26], [27]. As discussed previously, PM synchronous machines are attractive and desirable for ac drives due to the advantages of high power density and efficiency. However, the fixed field excitation provided by permanent magnets limits the controllability and high-speed capability of PMSM drives. Moreover, the current and voltage constraints of power inverter result in difficulties of current regulation and the decreased torque production as speed increases. To extend their operating speed ranges, PM motors are generally operated in such a way that the armature currents with large negative direct-axis component partially demagnetize the magnetic field and thus weaken the air-gap flux achieving the so-called flux weakening [28-30]. However, this approach involves the risk of demagnetizing the permanent magnets irreversibly and generates significant heat due to copper losses of stator windings. If the ambient temperature and the reverse flux are sufficiently high to move the magnetic operating point near or below the knee of normal demagnetization point, the permanent magnets will never be able to recoil back to the original operating point after the demagnetizing current is removed. Therefore, without demagnetizing the magnets, how to fully utilize the limited current and voltage capability of power inverter to extend the speed range of PMSM is always of great interest as well as a challenge [31]. To avoid the irreversible demagnetization of permanent magnets, many solutions have been reported in terms of various rotor structures of PM motors [31-33]. L. Xu et al. proposed a new design concept of PM machine for flux-weakening operation, which was aimed at minimizing the required demagnetizing current for a given level of flux weakening. By the way of altering the flux path of magnets, not only was the copper losses reduced but also the risk of damaging the permanent magnets eliminated [31]. Tapia et al. explored a magnetic structure termed the consequent-pole PM (CPPM) machine which had inherent field weakening capability. It was concluded that the machine combined the fixed excitation of rare-earth permanent magnet with the variable flux given by a field winding located on the stator, and thus the air-gap flux could be controlled over a wide range with minimum conduction losses and little demagnetization risk for the PM pieces [32]. In addition, comprehensive design methods were reviewed in [32]: 1) connecting groups of the stator winding in different configurations by which the induced voltage could be adjusted accordingly; 2) a stator-mounted PMSM where the flux weakening was operated by changing the reluctance path of the magnets; 3) using a field winding to add or subtract flux from the magnets; and 4) a PM motor with two-section rotor with field weakening where the reluctance of the direct-axis flux path was varied with changing the ratio between each section. Soong and Miller concluded that for the maximum torque field-weakening control, the optimal high-saliency interior PM motor design was most promising for applications requiring a wide field-weakening range [33]. The above efforts were made on the different types of PM motor design, which obviously resulted in the increased manufacturing cost due to the additional windings and/or complicated rotor structure. On the other hand, many control strategies and algorithms have been developed for flux-weakening operation of PMSM and published during the last decade [34-44]. Macminn and Jahns presented two control techniques to enhance the performance of IPM drives over an extended speed range. Although the proposed feed-forward current regulator compensation and flux-weakening control algorithms combine to improve the torque production capability of the IPM motor at high speeds, full effectiveness of the techniques strongly depends on accurate machine parameters used in control functions. And the control performance is degraded gracefully as errors between the programmed and actual parameters are increased [34]. Sebastian and Slemon [35] investigated the maximum torque per ampere (MTPA) operation of PMSM up to a break-point speed with optimum alignment of the stator and magnet field. Operation at higher speeds with reduced torque was achieved by the adjustment of current angle to reduce the effective magnet flux, i.e., the equivalent of field weakening. Dhaoudi and Mohan researched a current-regulated flux-weakening method by introducing a negative current component to create direct-axis flux in opposition to that of the rotor flux by magnets, resulting in a reduced air-gap flux. This armature reaction effect was used to extend the operating speed range of PMSM and relieve the current regulator from saturation that is subject to occurring at high speeds [36]. Similarly, not only a current vector control to expand the operating limits under the constant inverter capacity but also the improvement by the feed-forward decoupling compensation were proposed in [37], [38] respectively by Morimoto et al. In these flux-weakening schemes, the demagnetizing current command was calculated based on the mathematical model of the PM motor and, consequently, the performance of the PMSM drive system was strongly dependent on the motor parameters and sensitive to operating conditions. Sudhoff et al set forth a flux-weakening control for SPM motors, which was relatively simple and did not require the knowledge of the machine and inverter parameters. Moreover, the miscellaneous voltage drops such as semiconductors voltage drops, current sensor voltage drops, and those caused by the dead time in the switching strategy were automatically included into the calculation of the direct-axis current. The calculated direct-axis current command, i.e., demagnetizing current command, was proportional the current error of quadrature-axis current. Unfortunately, because the proposed feedback control is proportional, there always exists control error. Even though the error can be reduced by selecting high feedback gain, the control instability of the overall drive system would be a problem [39]. Sozer and Torrey [40] presented an approach for adaptive control of the surface mounted PM motor over its entire speed range. The adaptive flux-weakening scheme was able to determine the right amount of direct-axis current without knowing the load torque and inverter parameters. The level of demagnetizing current was obtained by using the current error between the actual and reference currents that gave a measure of inverter saturation. Integration of this error by an additional integrator with a forgetting factor drove the direct-axis current. Y. S. Kim et al, J. M. Kim et al and J. H. Song et al proposed a flux-weakening control method based on a voltage regulator using the voltage error signals between the allowable maximum output voltage and the voltage command [41-43]. The output of the voltage regulator determines the required amount of the demagnetizing current. In addition, the onset of flux weakening could be adjusted to prevent the saturation of the current regulators required by the vector control of PM motors.

Both current-error- and voltage-error-based flux-weakening control methods require an additional PI regulator or integrator to generate the demagnetizing current command, which, in turn, causes the increased complexity of the overall control system. Furthermore, the added controller could only operate properly under well-tuned conditions, which is not easily reached. Conventionally, two current regulators of the direct- and quadrature-axis current in the rotating reference frame are required to achieve the torque and flux control simultaneously as in [44]. Unfortunately the direct- and quadrature-axis current cannot be truly controlled independently due to their cross-coupling effects inside the PM motor. The cross-coupling effects will increase with rotor speed and become dominant in the high-speed range. As a result, the dynamic performance of current and torque response is degraded at high speeds without decoupling control. To control a PM motor with fast dynamic response, accurate speed regulation and high efficiency, it is necessary to know the rotor position for the implementation of vector control, or field-oriented control [41-47]. Adaptive control seems to be the most promising one of various modern control strategies reported in the literatures as [48], [49]. Cerruto et al proposed an adaptive control scheme, namely Model Reference Adaptive Control (MRAC), characterized by a reduced amount of computation. The MRAC approach was able to compensate the variations of the system parameters, such as inertia and torque constant. A disturbance torque observer was employed to balance the required load torque and reduce the complexity of the adaptive algorithm [48]. Baik et al investigated the MRAC-based adaptation mechanisms for the estimation of slowly varying parameters using the Lyapunov stability theory. A linearized and decoupled model was derived, which includes the influence of inertia variation and speed measurement error on the nonlinear speed control of PMSM [50]. Researches carried out in these references show that the adaptive control can improve the robustness of PMSM drives. However, system identification and state estimation require complex computations. Moreover, they are based on the assumption that the structure of the system model is specified and especially motor/load dynamics are well understood, which cannot be guaranteed in practice. And recently, T. Raminosoa et al. propose reluctance network modeling of surface permanent magnet motor considering iron nonlinearities. They present a simple, quick and precise nonlinear reluctance network modeling of an in-wheel surface permanent magnet motor. The saturation of the ferromagnetic materials is considered and a simple air-gap length function is used to take the slotting effect into account. The topology and the reluctance values of the air-gap network are automatically computed for any rotor position. Thus, the proposed technique allows a steady state time stepping simulation. Moreover, the model accurately predicts the effect of the demagnetization. The proposed model can be advantageously used for a geometry optimization as well as for the diagnosis of demagnetization [51]. A. Rostami, and B. Asaei introduce a novel method for estimating the initial rotor position of PM motors without the position sensor. In their paper, a novel method to detect the initial rotor position of the PM motors is proposed, first, by using a space vector model, response of the stator current space vector to the saturation of the stator core is analyzed; then a novel method based on the saturation effect is presented that estimates the initial rotor position and the maximum estimation error is less than 3.8%. Simulation results confirm this method is effective and precise, and variation of the motor parameters does not affect its precision [52]. Ying-Yi Hong et al. present MPPT for PM wind generator using gradient approximation. They apply new maximum-power-point tracking (MPPT) algorithms to a wind-turbine generator system (WTGS). In their work, the WTGS is a direct-drive system and includes the wind-turbine, permanent-magnet (PM) synchronous generator, three-phase full bridge rectifier, buck-boost converter and load. The new MPPT method uses gradient approximation (GA) algorithm. Three methods based on GA for achieving MPPT are discussed in this paper: (1) full-sensor control with anemometer and tachometer, (2) rule-based method and (3) adaptive duty cycle method.

The third method has merits of no PID parameters, proportional constant, anemometer, tachometer and characteristics of WTGS required. This method enables the permanent-magnet synchronous generator (PMSG) to operate at variable speeds to achieve good performance. Simulation results show that the tip-speed ratio (TSR) and power coefficient obtained by the adaptive duty cycle method with GA can be almost identical to the optimal values [53]. In 2010, M.S. Merzoug et al., propose nonlinear back-stepping control of Permanent Magnet Synchronous Motor (PMSM) This research presents a novel speed control technique for an permanent magnets synchronous drive based on newly Nonlinear back-stepping technique. The most appealing point of it is to use the virtual control variable to make the high-order system simple, and thus the final control outputs can be derived step by step through appropriate Lyapunov functions back-stepping control approach is adapted to derive the control scheme, which is robust to parameter uncertainties and external load disturbance. Simulation results clearly show that the proposed controller can track the speed reference signal successfully under parameter uncertainties and load torque disturbance rejection [54]. Also in 2010, Jinpeng Yu et al., introduce a research about adaptive fuzzy tracking control for a Permanent Magnet Synchronous Motor via back-stepping approach. In this study, fuzzy logic systems are used to approximate nonlinearities, and an adaptive back-stepping technique is employed to construct controllers. The proposed controller guarantees the tracking error convergence to a small neighborhood of the origin and achieves the good tracking performance. Simulation results clearly show that the proposed control scheme can track the position reference signal generated by a reference model successfully under parameter uncertainties and load torque disturbance without singularity and over-parameterization [55]. Hasanien in 2010 too, presents a digital observer controller for permanent magnet synchronous motor (PMSM). The digital observer controller is used for torque ripple minimization of this type of motors. The proposed controller is a newly applied of PMSM. The dynamic response of the (PMSM) with the proposed controller is studied during the starting process under the full load torque and under load disturbance. The effectiveness of the proposed digital observer controller is then compared with that of the conventional PI controller. Experimental results are presented to demonstrate the validity and effectiveness of the proposed control scheme [56]. And finally, Li Dong et al, in 2010 investigate the stability of a PMSM with parameter uncertainties. After uncertain matrices which represent the variable system parameters are formulated through matrix analysis, a novel asymptotical stability criterion is established by employing the method of Lyapunov functions and linear matrix inequality technology. An example is also given to illustrate the effectiveness of our results [57].

High speed PM machines allow for a reduced system weight, higher operating efficiency, reduced maintenance costs and a smaller envelope than a conventional solution in the same power rating. However, with the higher power density and frequency also comes higher power loss density. Special attention must then be paid to the choice of lamination material, coil construction, and cooling mechanism for what would otherwise be a typical stator and housing design. In the case of a high speed PM motor, temperature sensitivity of the magnet material is an additional factor. For this reason, Samarium Cobalt is often the choice to realize higher temperature designs [58]. R. A. Ahmad, et. al, presented a system based on using high speed permanent magnet synchronous generators driven by gas turbines as prime movers and DC distribution with local conversion at the load points [58]. S. Scridon, et. al, designed, optimized and tested new generator, good power / volume and superior efficiency (up to 80%) are obtained at costs comparable to those of existing Lundell generator [59]. A. Binder, et. al, investigated that, during the design procedure of high- speed electrical machines, special attention needs to be paid to mechanical design. FE calculations for the mechanical strength of the rotor structure are recommended, for simple but realistic rotor structures, analytical approaches lead to satisfying results. This holds true both for surface mounted and specially selected buried-magnet-type rotors. The fixation of magnets in surface-mounted and buried magnet-type high-speed permanent-magnet machines is compared for the same motor data, showing that for high-speed operation (e.g., 40 000 r/min, 40 kW), surface-mounted magnets fixed by a Carbon-fiber bandage are the better choice, as they incorporate much higher mechanical strength, allowing higher maximum speed [60]. J.L.F. van der Veen, et. al, demonstrated that, the design of a high-speed 1400 kW synchronous generator with permanent magnet excitation and loaded by a rectifier, it became apparent that rotor losses are a major problem. An approximate solution for the rotor losses caused by the asynchronous field components has been derived. The formulae show the effects of machine dimensions and harmonics and the effect of a conducting shield in the rotor. The main purpose of the study is to have a tool for making an early choice among several stator winding configurations. Also, verifying that, it possible to reduce the rotor losses to an acceptable level, e.g. 0.1 - 0.2% of the rated power. Consequently, the cooling of the rotor to an acceptable temperature level is feasible [61]. S. R. Guda, et. al, introduce modeling and simulation of a micro turbine generation system suitable for isolated as well as grid-connected operation. The system comprises of a permanent magnet synchronous generator driven by a micro turbine. A description of the overall system is given and mathematical models for the micro turbine and permanent magnet synchronous generator are presented. Simulation results show that the developed model has the ability to meet the requirements of the load. Simulation studies have been carried out in MATLAB/Simulink under different load conditions [62]. S. M. Hosseini, et. al, proposed the design, prototyping, and analysis of a relatively small and cheap axial-flux three-phase coreless permanent magnet generator. With the finite - element analysis, the parameters of the generator were calculated. The prototyped generator is relatively small and cheap [63]. P.H. Mellor, et. al., introduced a good idea about, a permanent machine with a hybrid rotor construction for an aircraft emergency generator application, designed to be capable of generating a constant 20 kW over a wide 3,000 to 36,000 rpm speed range. Initial testing of the prototype machine has indicated a performance close to the design requirements. A maximum generating system efficiency of 84% was obtained at the desired 20 kW output (accounting for the combined mechanical, electrical machine and power electronic losses) [64]. M. Sadeghierad, et. al, illustrated that, high – speed axial flux machine eligible for distributed generating application due to its compactness and lightness. Also, due to the high rotor speed and high frequency of the stator winding current, the design of a high – speed generator is much difficult and quite different from designing a low speed conventional generator. The efficiency, total power, with a number of critical design parameters, including magnet material (Br), air gap, and outer diameter of machine were presented [65]. D. P. Arnold, et. al, presented the design, fabrication, and characterization of permanent – magnet (PM) generators for use in micro scale power generation systems. The generators are three phase axial-flux synchronous machines, each consisting of an eight – pole surface – wound stator and PM rotor. At a rotational speed of 120 000 rpm, one generator demonstrates 2.5 W of mechanical – to – electrical power conversion and, coupled to a transformer and rectifier, delivers 1.1 W of dc electrical power to a resistive load [66]. A. Binder, et. al, provided that, high – speed applications involve technical and economical advantages because, as direct drives, they avoid the gear as an additional mechanical drive component. Because, permanent –magnet synchronous machines (PMSMs) are attracting growing attention for high – speed drives. The fixation of magnets in surface – mounted and buried magnet – type high – speed permanent – magnet machines is compared for the same motor data, showing that for high – speed operation (e.g., 40 000 r/min, 40 kW), surface – mounted magnets fixed by a carbon-fiber bandage are the better choice, as they incorporate much higher mechanical strength, allowing higher maximum speed [67]. During the design procedure of high-speed electrical machines, special attention needs to be paid to mechanical design issues. J. H. Paulides, et. al, introduced the influence of the choice of stator lamination material on the iron loss in a high speed, high power permanent magnet generator, which is interfaced to a DC link via a simple bridge rectifier. The potential benefit, in terms of reduced iron loss, by employing 6.5% SiFe laminations in a representative high speed, high power permanent magnet generator, whose output is rectified by a simple bridge rectifier, has been quantified. The rating of the generator is representative of machines which would be employed in 'more – electric' ships and for embedded power generation [68]. T. S. El – Hasan, et. al, introduced a design methodology for a modular high – speed PM axial – flux generator from first principles is illustrated with a case study on a 50 kVA, 420 V, 3 – phase, 50 000 rpm PM generator. Optimization of the design parameters is shown. In their paper, a good first degree of approximation is achieved by examining the variations of efficiency with different parameters. An efficiency of 92% in this proposed design, considerably superior to conventional low speed generators, has been achieved where iron losses have been eliminated, and others have been minimized by proper selection of design parameters [69]. S. M. Jang, et. al, deled with the rotor losses in the high – speed permanent magnet (PM) synchronous alternator for distributed power generation system. Because, an optimum design of PM machines requires an accurate prediction for these rotor losses. On the basis of analytical field analysis and two - dimensional finite element analysis, this study predicts the flux harmonics and rotor losses in the PM alternator considering the rectifier load [70]. C. C. Hwang, et. al., proposed a method affects as a tool in designing a high - speed, surface permanent magnet generator with large air gap length. Alnico magnets are used for field excitation. Steady – state performance is analyzed by finite element (FE) method. Experimental tests are conducted to verify the FEM predictions [71]. Z. Kolondzovski, Purposed the thermal design of high – speed electrical machines because, they have a greater challenge in comparison with conventional electrical machines. He deduced that, from the critical thermal operation analysis, it can be concluded that, the magnets cannot be effectively cooled only by the air flow in the air gap if there is not a shield from eddy – currents. Also, he aimed to perform thermal analysis for different rotor types according to the level of shield from eddy currents in order to achieve a safe thermal design of the machine. The practical significance of the paper is beneficial for the designers of high – speed PM electrical machines [72]. F. Sahin, et. al, summarized the critical aspects concerning the design, manufacturing and testing of a high – speed axial – flux permanent – magnet machine which will be applied in a hybrid electric vehicle application. Analysis of the losses and the thermal behavior of the machine are included. Mechanical constraints and the aspects of manufacturing are also summarized [73]. The outside diameter, inside-to-outside diameter ratio, number of slots, magnet span, magnet skewing, and stator offsetting affect the performance of the machine to greater or lesser extents, and need to be carefully chosen to obtain an optimal design. These choices are discussed in detail by Vandenput, et. al. [74]. A. S. Nagorny, et. al, presented design considerations of a high speed, high efficiency permanent magnet synchronous machine for use as a flywheel motor/generator. The surface mounted magnet rotor topology shows a higher output power together with an acceptable back emf total harmonic distortion level. The finite element method allows more detailed examination of the demagnetization of the permanent magnets due to the stator currents and provides more accuracy than the conventional method. The ability of the SmCo permanent magnets to withstand the high speed operation can be increased by segmenting the magnet pole. The parallel magnetic field orientation shows lower cogging torque level compared to the radial one [75]. As discussed by several researchers, stator inner and outer diameters are the two most important design parameters. Hence, for cases where the stator outer diameter is limited or imposed by the rest of the system, the ratio of inner to outer diameter, Kr is the key parameter to consider and it has a crucial impact on the determination of the machine characteristics, such as torque, torque to weight ratio, iron losses, copper losses, and efficiency. Caricchi et. al. [76] shows the dependency on Kr for designs with various numbers of pole pairs. Other important design parameters are the pole number, magnet thickness, conductor size, number of turns and material types. On the other hand, every design has its particular constraints and they differ with the type of application. Generally, one tries to obtain the maximum torque for a given motor diameter at a given speed. Mostly for small machines, the number of poles is limited due to the reduced space available for the windings. Nevertheless, the most restricting limitation for the number of poles is the motor operating speed. If the speed is high, a large number of poles will bring about an increase in the frequency, which directly leads to higher stator core losses and higher converter losses. The volume, thickness, shape and type of the permanent magnets also affect both the performance and the cost of the machine. The relationship between magnet volume and torque is explained in detail in [77]. In reference [78], a design based on the optimization of the width of the permanent magnets for a surface-mounted permanent-magnet type axial-flux machine is explained. The choice of the permanent magnet width to pole pitch ratio is discussed. For higher values of this ratio, 1 for instance, flux linkage is maximum, but also flux leakage due to adjacent permanent magnets is high. By decreasing the permanent magnet width, linkage and leakage fluxes are both decreased though not proportionally. Since the permanent magnets are the most expensive part of the machine, instead of Ne- Fe-B, ferrite magnets are used in some works. Also, ferrites having small conductivity, do not suffer from eddy current problems which emerge in sintered rare-earth magnets [79]. But, of course, ferrite has poor characteristics when compared with Ne-Fe- B, and its usage makes it impossible to obtain high air gap flux densities. Magnet protection must also be considered as a constraint together with the dimensional machine parameters [80]. Additionally, high temperature introduces extra constraints on the choice of the materials. Other constraints to be considered are mainly of mechanical nature. The centrifugal force acting on a rotating mass is proportional to the velocity squared and inversely proportional to the radius of rotation. Consequently, for high-speed applications (speeds in excess of 10000 rpm) the rotor must be designed with a small diameter in order to reduce tensile stress, and must have a very high mechanical integrity [81]. Pillay et al., presented a literature survey on PM ac motors and drives showing some aspects regarding design and control [82]. A comparative study of different designs in terms of dimensions and torque capability is presented in [83]. A general method for sizing of electric machines that highlights the need of relating the design with the type of converter used is shown in [84]. Extensive aspects of PM motor technology and design of brushless dc machines are presented in [85] and [86]. Finally, the author himself with others contributed in this trend to improve the PM m/c performance through improve the performance by proper modeling, control, optimization, using genetic, neural network and design.

REFERENCES

[1] R. Monajemy, "Control Strategies and Parameter Compensation for Permanent Magnet Synchronous Motor Drives," in Faculty of the Virginia Polytechnic Institute and State University, PhD: 2000.

[2] R. Krishnan, Electric Motor Drives: Modeling, Analysis & Control, Prentice Hall, 2006.

[3] B. K. Bose, Power Electronics and Variable Frequency Drives, 1 ed: Wiley, John & Sons, 1996.

[4] M. Aydin, "Axial Flux Mounted Permanent Magnet Disk Motors For Smooth Torque Traction Drive Application," in Electrical and Computer Engineering, vol. PhD: University of Wisconsin 2004.

[5] B. K. Bose, Modern power electronics and AC drives: Prentice Hall, 2002.

[6] S. Evershed, “Permanent Magnets in Theory and Practice”, IEE Journal, Vol 58, No. 295, 1920.
[7] S. Evershed, “Permanent Magnets in Theory and Practice”, IEE Journal, Vol 63, No. 344, 1925.
[8] W. Kober, “Permanent Magnet Alternators”, Report E-1004, Signal Corps Engineering Laboratories, Bradley Beach, N. J., Sept 16, 1946.
[9] R. M. Saunders, R. H. Weakley, “Design of Permanent Magnet Alternators”, AIEE transactions, Vol 70, part II, 1951, pages 1578-1581.
[10] T. Sebastian, G. Slemon, and M. Rahman, "Modelling of permanent magnet synchronous motors," Magnetics, IEEE Transactions on, vol. 22, pp. 1069-1071,1986.
[11] T. M. Jahns, G. B.Kliman, and T. W. Neumann, "Interior Permanent-Magnet Synchronous Motors for Adjustable-Speed Drives," Industrial Applications, IEEE Transactions on, vol. IA-22, pp. 738-746, 1986.
[12] P. Pillay and R. Krishnan, "Modeling of permanent magnet motor drives," Industrial Electronics, IEEE Transactions on, vol. 35, pp. 537-541, 1988.
[13] P. Pillay and R. Krishnan, "Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive," Industry Applications, IEEE Transactions on, vol. 25, pp. 265-273, 1989.
[14] S. Morimoto, Y. Tong, Y. Takeda, and T. Hirasa, "Loss minimization control of permanent magnet synchronous motor drives," Industrial Electronics, IEEE Transactions on, vol. 41, pp. 511-517, 1994.
[15] A. H. Wijenayake and P. B. Schmidt, "Modeling and analysis of permanent magnet synchronous motor by taking saturation and core loss into account," 1997.
[16] K. Jang-Mok and S. Seung-Ki, "Speed control of interior permanent magnet synchronous motor drive for the flux weakening operation," Industry Applications,IEEE Transactions on, vol. 33, pp. 43-48, 1997.
[17] B. Cui, J. Zhou, and Z. Ren, "Modeling and simulation of permanent magnet synchronous motor drives," 2001.
[18] C. Mademlis and N. Margaris, "Loss minimization in vector-controlled interior permanent-magnet synchronous motor drives," Industrial Electronics, IEEE Transactions on, vol. 49, pp. 1344-1347, 2002.
[19] X. Jian-Xin, S. K. Panda, P. Ya-Jun, L. Tong Heng, and B. H. Lam, "A modular control scheme for PMSM speed control with pulsating torque minimization," Industrial Electronics, IEEE Transactions on, vol. 51, pp. 526-536, 2004.
[20] Peter Vas, Sensorless and Direct Torque Control, 1st Edition, Oxford University Press, 1998.
[21] R. Gabriel, W. Leonhard, and C. Nordby, “Field oriented control of standard AC motor using microprocessor,” IEEE Trans. Ind. Applicat., vol. IA-16, pp. 186–192, 1980.
[22] L. Harnefors, “Design and analysis of general rotor-flux oriented vector control systems,” IEEE Trans. Ind. Electron., vol. 48, pp. 383–389, Apr. 2001.
[23] M. Schroedl, “Sensorless control of AC machines at low speed and standstill based on the “INFORM” method,” in Conf. Rec. IEEE-IAS Annu. Meeting, vol. 1, 1996, pp. 270–277.
[24] P. L. Jansen and R. D. Lorentz, “Transducerless position and velocity estimation in induction and salient AC machines,” IEEE Trans. Ind. Applicat., vol. 31, pp. 240–247, Mar./Apr. 1995.
[25] P. L. Jansen, R. D. Lorenz, and D. W. Novotny, “Observer-based direct field orientation: Analysis and comparison of alternative methods,” IEEE Trans. Ind. Applicat., vol. 30, pp. 945–953, July/Aug. 1994.
[26] T. M. Jahns and V. Blasko, “Recent advances in power electronics technology for industrial and traction machine drives,” Proc. IEEE, vol. 89, pp. 963–975, June 2001.
[27] Thomas M. Jahns, “Motion control with permanent-magnet ac machines,” in Proc. IEEE, vol. 82, Aug. 1994, pp. 1241-1252.
[28] T. M. Jahns “Flux-weakening regiem operation of an interior permanent-magnet synchronous motor drives,” IEEE Trans. Ind. Applicat., vol. IA-23, pp. 681-689, July/Aug. 1987.
[29] B. Sneyers, D. W. Novotny and T. A. Lipo, “Field weakening in buried permanent magnet ac motor drives,” IEEE Trans. Ind. Applicat., vol. IA-21, pp. 398-407, Mar./Apr. 1991.
[30] T. M. Jahns, G. B. Kliman and T. W. Neumann, “Interior permanent-magnet synchronous motors for adjustable-speed drive,” IEEE Trans. Ind. Applicat., vol. IA-22, pp. 738-747, July/Aug. 1986.

[31] L. Xu, L. Ye, L. Zhen and A. El-Antably, "A new design concept of permanent magnet machine for flux weakening operation," IEEE Trans. Ind. Applicat., vol. 31, pp. 373-378, March/April, 1995.

[32] J. A. Tapia, F. Leonardi, and T. A. Lipo, "Consequent-pole permanent-magnet machine with extended field-weakening capability," IEEE Trans. Ind. Applicat.,vol. 39, pp. 1704-1709, Nov./Dec., 2003.

[33] W. L. Soong and T. J. Miller, "Field-weakening performance of brushless synchronous AC motor drives," Proc. IEE—Elect. Power Applicat., vol. 141, no. 6, pp. 331–340, Nov. 1994.

[34] S. R. Macminn and T. M. Jahns, "Control techniques for improved high-speed performance of interior PM synchronous motor drives," IEEE Trans. Ind. Applicat., vol. 2, pp. 997-1004, Sept./Oct. 1991.

[35] T. Sebastian and G. R. Slemon, "Operating limits of inverter-driven permanent magnet motor drives," IEEE CH2272-3/86, pp. 800-805, 1986.

[36] R. Dhaouadi and N. Mohan, "Analysis of current-regulated voltage-source inverters for permanent magnet synchronous motor drives in normal and extended speed ranges," IEEE Trans. Energy Conv., vol. 5, pp. 137-144, Mar. 1990.

[37] S. Morimoto, M. Sanada and K. Takeda, "Wide-speed operation of interior permanent magnet synchronous motors with high-performance current regulator," IEEE Trans. Ind. Applicat., vol. 30, pp. 920-926, July/Aug. 1994.

[38] S. Morimoto, Y. Takeda, T. Hirasa, and K. Taniguchi, "Expansion of operating limits for permanent magnet by current vector control considering inverter capacity," IEEE Trans. Ind. Applicat., vol. 26, pp. 866-871, Sept./Oct. 1990.

[39] S. D. Sudhoff, K. A. Corzine and H. J. Hegner, "A flux-weakening strategy for current-regulated surface-mounted permanent-magnet machine drives," IEEE Trans. Energy Conv., vol. 10, pp. 431-437, Sept. 1995.

[40] Y. Sozer and D. A. Torrey, "Adaptive Flux weakening control of permanent magnet synchronous motors," in Conf. Rec. IEEE-IAS Annu. Meeting, vol. 1, St. Louis, MO, 1998, pp. 475–482.

[41] Y. S. Kim, Y. K. Choi and J. H. Lee, "Speed-sensorless vector control for permanent-magnet synchronous motors based on instantaneous reactive power in the wide-speed region," IEE Proc-Electr. Power Appl., vol. 152, No. 5, pp. 1343-1349, Sept. 2005.

[42] J. M. Kim and S. K. Sul, "Speed control of interior permanent magnet synchronous motor drive for the flux weakening operation," IEEE Trans. Ind. Applicat., vol. 33, pp. 43-48, Jan./Feb. 1997.

[43] J. H. Song, J. M. Kim, and S. K. Sul, "A new robust SPMSM control to parameter variations in flux weakening region," IEEE IECON, vol. 2, pp. 1193-1198, 1996.

[44] J. J. Chen and K. P. Chin, "Automatic flux-weakening control of permanent magnet synchronous motors using a reduced-order controller," IEEE Trans. Power Electron., vol. 15, pp. 881-890, Sept. 2000.

[45] A. Consoli, G. Scarcella and A. Testa, "Industry application of zero-speed sensorless control techniques for PM synchronous motors," IEEE Trans. Ind.Applicat., vol. 37, pp. 513-521, March/April, 2001.

[46] M. Tursini, R. Petrella and F. Parasiliti, "Initial rotor position estimation method for PM motors," IEEE Trans. Ind. Applicat., vol. 39, pp. 1630-1640, Nov./Dec., 2003.

[47] F. J. Lin and S. L. Chiu, "Adaptive fuzzy sliding mode control for PM synchronous servo motor drives," Proc. IEE—Contr. Theory Applicat., vol. 145, no. 1, pp. 63–72, 1998.

[48] E. Cerruto, A. Consoli, A. Raciti, and A. Testa, "A robust adaptive controller for PM motor drives in robotic applications," IEEE Trans. Power Electron., vol. 10, pp. 62-71, Jan. 1995.

[49] K. J. Åström and B. Wittenmark, "A survey of adaptive control applications," in Proc. 34th IEEE Conf. Decision and Control New Orleans, LA, 1995, pp. 649-654.

[50] I. C. Baik, K. H. Kim, and M. J. Youn, "Robust nonlinear speed control of PM synchronous motor using adaptive and sliding mode control techniques," Proc. IEE—Elect. Power Applicat., vol. 145, no. 4, pp. 369–376, 1998.

[51] T. Raminosoa, J.A. Farooq, A. Djerdir and A. Miraoui, "Reluctance network modelling of surface permanent magnet motor considering iron nonlinearities," Energy Conversion and Management, Vol. 50, (2009), pp. 1356–1361.

[52] Alireza Rostami and Behzad Asaei, "A novel method for estimating the initial rotor position of PM motors without the position sensor," Energy Conversion and Management, Vol. 50, (2009), pp. 1879–1883.
[53] Ying-Yi Hong, Shiue-Der Lu and Ching-Sheng Chiou, "MPPT for PM wind generator using gradient approximation," Energy Conversion and Management, Vol. 50, (2009), pp. 82–89.
[54] M.S. Merzoug and H. Benalla, "Nonlinear Backstepping Control of Permanent Magnet Synchronous Motor (PMSM)," International Journal of Systems Control (Vol.1-2010/Iss.1,),pp. 30-34.
[55] Jinpeng Yu, Junwei Gao, Yumei Ma, and Haisheng Yu, "Adaptive Fuzzy Tracking Control for a Permanent Magnet Synchronous Motor via Backstepping Approach," Mathematical Problems in Engineering, Hindawi Publishing Corporation, Volume 2010, Article ID 391846.
[56] H.M. Hasanien, "Torque ripple minimization of permanent magnet synchronous motor using digital observer controller," Energy Conversion and Management, Volume 51, issue 1 (January, 2010), pp. 98-104
[57] Li Dong, Wang Shi-Long, Zhang Xiao-Hong and Yang Dan, "Impulsive control for permanent magnet synchronous motors with uncertainties: LMI approach," Chinese Physics B, Vol.19,Issue1,pp.010506-7(2010).
[58] R. A. Ahmad, Z. Pan, and D. M. Saban, "On-Board Electrical Network Topology Using High Speed Permanent Magnet Generators" 1-4244- 0947-0/07 © 2007 IEEE, pp. 356 – 362.
[59] S. Scridon, I. Boldea, L. Tutelea, F. Blaabjerg, and E. Ritchie, "BEGA – A Biaxial Excitation Generator for Automobiles: Comprehensive Characterization and Test Results" IAS, 2004, 2 0-7803-8486- 5/04/ © 2004 IEEE, pp. 1682 – 1690.
[60] A. Binder, T. Schneider, and M. Klohr, "Fixation of Buried and Surface- Mounted Magnets in High-Speed Permanent-Magnet Synchronous Machines", IEEE Trans. On Industry Applications, Vol. 42, NO. 4, July/August, 2006, pp. 1031 - 1037.
[61] J.L.F. van der Veen, L.J.J. Offringa, and A. J .A. Vandenput, " Minimizing rotor losses in high-speed high-power permanent magnet Synchronous generators with rectifier load", IEE Proc-Electr. Power Appl., Vol. 144, No. 5, September 1997, pp. 331- 337.
[62] S. R. Guda, C. Wang, and M. H. Nehrir, "A Simulink – Based Micro turbine Model for Distributed Generation Studies", 0-7803-9255-8/05/, 2005 IEEE, pp. 269 – 274.
[63] S. M. Hosseini, M. A. Mirsalim, and M. Mirzaei1, "Design, Prototyping, and Analysis of a Low Cost Axial-Flux Coreless Permanent-Magnet Generator", IEEE Trans. On Magnetics, Vol. 44, No. 1, January 2008, pp. 75 – 80.
[64] P.H. Mellor, S.G. Burrow, T. Sawata, and M. Holme, "A Wide – Speed – Range Hybrid Variable – Reluctance / Permanent – Magnet Generator for Future Embedded Aircraft Generation Systems", IEEE Trans. On Industry Applications, Vol. 41, No. 2, March/April 2005, PP. 551 – 556.
[65] M. Sadeghierad, H. Lesani, H. Monsef, and A. Darabi, "Design considerations of High Speed Axial Flux permanent magnet Generator with Coreless Stator", The 8th International Power Engineering Conference (IPEC 2007), pp. 1098 – 1102.
[66] D. P. Arnold, S. Das, J. W. Park, I. Zana, J. H. Lang, and M. G. Allen, "Micro fabricated High-Speed Axial-Flux Multi watt Permanent- Magnet Generators—Part II: Design, Fabrication, and Testing", Journal Of Micro Electromechanical Systems, Vol. 15, No. 5, October 2006. pp. 1351 – 1363.
[67] A. Binder, T. Schneider, and M. Klohr, "Fixation of Buried and Surface-Mounted Magnets in High-Speed Permanent - Magnet Synchronous Machines", IEEE Trans. On Industry Applications, Vol. 42, No. 4, July/August 2006, pp. 1031 – 1037.
[68] J. J. H. Paulides, G. W. Jewell, and D. Howe, "An Evaluation of Alternative Stator Lamination Materials for a High – Speed, 1.5 MW, Permanent Magnet Generator", IEEE Trans. On Magnetics, Vol. 40, No. 4, July 2004, pp. 2041 - 2043.
[69] T. S. El – Hasan, P. C. K. Luk, F. S. Bhinder, and M. S. Ebaid, "Modular Design of High – Speed Permanent – Magnet Axial – Flux Generators", IEEE Trans. On Magnetics, Vol. 36, No. 5, September 2000, pp. 3558 – 3561.
[70] S. M. Jang, H. W. Cho, and Y. H. Jeong, "Influence on the rectifiers of rotor losses in high – speed permanent magnet synchronous alternator", Journal of Applied Physics, 08R315 (2006), American Institute of Physics, 08R315-1 - 08R315-3.

[71] C. C. Hwang, C. L. Tien, and H. C. Chang, "Performance and applications of a small PM generator", phys. stat. sol. (c) 4, No. 12, pp. 4635 – 4638 (2007) / DOI 10.1002/pssc.200777418, Published online 18 December 2007.

[72] Z. Kolondzovski, "Determination of critical thermal operations for High – speed permanent magnet electrical machines", The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 27 No. 4, 2008, pp. 720-727, Emerald Group Publishing Limited. The current issue and full text archive of this journal is available at www.emeraldinsight.com/0332-1649.htm

[73] F. Sahin and A.J.A. Vandenput, "Thermal modeling and testing of a High – speed axial – flux permanent – magnet machine", The International Journal for Computation and Mathematics in Electrical and Electronic Eng., Vol. 22 No. 4, 2003, pp. 982 – 997. The current issue and full text archive of this journal is available at http://www.emeraldinsight.com/0332-1649.htm.

[74] A.J.A. Vandenput and F. Sahin, "Design considerations of the flywheel-mounted axial-flux permanent-magnet machine for a hybrid electric vehicle", 8th European Conference on Power Electronics and Applications.

[75] A. S. Nagorny, N. V. Dravid, R. H. Jansen, and B. H. Kenny, "Design Aspects of a High Speed Permanent Magnet Synchronous Motor / Generator for Flywheel Applications", NASA/TM—2005-213651 June 2005, International Electric Machines and Drives Conference sponsored by the IEEE Industry Applications Society, IEEE Power Electronics Society, IEEE Power Engineering Society, and IEEE Industrial Electronics Society, San Antonio, Texas, May 15–18, 2005.

[76] F. Caricchi, F. Crescimbini, F. Mezzetti, and E. Santini, "Multistage axial flux PM machine for wheel direct drive", IEEE Trans. on Industry Applications, 32(4):882—887, July 1996.

[77] K.J. Binns and D.W. Shimmin, "Relationship between rated torque and size of permanent magnet machines. IEE Proc. Electr. Power Appl., 143(6):417—422, November 1996.

[78] F. Caricchi, F. Crescimbini, A. Di Napoli, and M. Marcheggiani, "Prototype of electric vehicle drive with twin water cooled wheel direct drive motors", PESC'96, 2:1926—1932, 1996.

[79] J. Jensen, F. Profumo, and A. Tenconi, "A low loss permanent magnet brushless DC motor utilizing tape-wound amorphous iron", IEEE Industry Applications Society Annual Meeting, pages 281—286, 1990.

[80] G.R. Slemon, "On the design of a high-performance surface-mounted PM motors", IEEE Trans. on Industry Applications, 30(1):134—140, January/February 1994.

[81] J. F. Gieras and M. Wing, "Permanent Magnet Motor Technology, Design and Applications", Marcel Dekker, Inc., 1997.

[82] P. Pillay and P. Freere, "Literature survey of permanent magnet AC motors and drives," IEEE IAS Annu. Meeting Conf. Rec., pt. 1, pp. 74–84, Oct. 1989.

[83] K. J. Binns and D.W. Shimmin, "The relationship between performance characteristics and size of permanent magnet motors," in Proc. 1995 Elect. Mach. Drives Conf., pp. 423–427.

[84] S. Huang, J. Luo, F. Leonardi, and T. Lipo, "A general approach to sizing and power density equations for comparison of electrical machines", IEEE Trans. Energy Conversion, vol. 34, pp. 92–97, Mar. 1998.

[85] D. C. Hanselmann, "Brushless Permanent Magnet Motor Design", New York: McGraw-Hill, 1994.

[86] J. R. Hendershot and T. J. E. Miller, "Design of Brushless Permanent Magnet Motors", Oxford, U.K.: Magna Physics Publishing and Clarendon Press, 1994.

[87] Adel El Shahat and Ali Keyhani, "Chapter 6: Sizing High Speed Micro Generators for Smart Grid Systems", Smart power Grids 2011 Book, Series: Power Systems, ISBN 978-3-642-21577-3, Springer-Verlag Berlin Heidelberg 2012, pp. 177–234.

[88] Adel El Shahat, Ali Keyhani, and Hamed El Shewy, "Sizing a High Speed PM Generator for Green Energy Applications, Journal of Electrical Systems (JES), ISSN 1112-5209; Vol. 6, Issue 4, December 2010.

[89] A. El Shahat, A. Keyhani and H. El Shewy, "400 kW Six Analytical High Speed Generator Designs for Smart Grid Systems", International Journal of Energy and Power Engineering, 3:4 2010 ; article 32, Vol. 3, No. 4, Autumn 2010, pp. 210 – 227.

[90] A. El Shahat, H. El Shewy, "PM Synchronous Motor Drive System for Automotive Applications", Journal of Electrical Systems (JES), ISSN 1112-5209; Vol. 6, Issue 2, June 2010.

[91] Adel El Shahat, Hamed El Shewy, “PM Synchronous Motor Dynamic Modeling with Genetic Algorithm Performance Improvement”, International Journal of Engineering, ISSN 2141-2839 (Online); ISSN 2141-2820 (Print); Science and Technology Vol. 2, No. 2, 2010, pp. 93-106.
[92] Adel El Shahat, and Hamed El Shewy, “High Fundamental Frequency PM Synchronous Motor Design Neural Regression Function”, Journal of Electrical Engineering, ISSN 1582-4594; Article 10.1.14, Edition 1, March, Vol. 10 / 2010.
[93] A. El Shahat, and H. El Shewy, “PM Synchronous Motor Control Strategies with Their Neural Network Regression Functions”, Journal of Electrical Systems (JES), ISSN 1112-5209; Vol. 5, Issue 4, Dec. 2009.
[94] H. M. El Shewy, F. E. Abd Al Kader, M. El Kholy, and A. El Shahat,“ Dynamic Modeling of Permanent Magnet Synchronous Motor Using MATLAB - Simulink” EE108, 6th International Conference on Electrical Engineering ICEENG 6, 27-29 May 2008, Military Technical College, Egypt .