PM Synchronous Generators with Hybrid Excitation Systems and Voltage Control Capabilities: a Review

Jacek F. Gieras

***Abstract* -- A brief review of permanent magnet (PM) synchronous generators with hybrid field excitation systems and output voltage regulation capabilities has been presented. Both series and parallel hybrid field excitation systems have been discussed. The review emphasizes the construction, advantages, drawbacks and basic characteristics of PM synchronous generators with additional field excitation winding placed either on the stator or rotor.**

***Index Terms*--Synchronous generators, permanent magnet machines, field, magnetic flux, excitation, voltage, control, regulation, review**

I. Introduction

In many variable-speed generator applications, as for example aircrafts, automobiles, wind turbines, microturbines, etc., constant-voltage operation over a broad range of speeds is required. Using classical synchronous machines with *wound rotor* and *electromagnetic excitation*, the required operating mode is achieved by appropriate reduction of the field excitation current as the speed increases. Permanent magnet (PM) brushless machines provide constant excitation flux that can only be controlled from the stator side, i.e., by injecting the *d*-axis current which in turn produces the *d*-axis armature reaction flux in opposite direction to the excitation flux [8,17].

The stator magnetic flux called also armature reaction flux in PM brushless machines can be controlled by means of the solid state converter. This operation may lead to a significant increase in winding losses and decrease in machine efficiency. The stator flux control is not possible if the solid state converter present in the energy conversion chain is not a controllable device. This is the case of a PM synchronous generator loaded with a passive diode rectifier.

Additional field excitation winding placed on the stator or rotor of a PM synchronous machines allows for direct adjusting the magnetic flux to given operating conditions.

II. Hybrid Excitation Systems for Synchronous Machines

A hybrid excitation system for a synchronous machine means that the excitation system consists of two or more subsystems. In most cases there are only two field excitation subsystems: (1) PMs and (2) field excitation winding fed with a d.c. current. In principle, hybrid field excitation systems can be classified with respect to paths for magnetic fluxes [1], i.e.:

(a) *series system,* in which the fluxes produced by PMs and d.c. winding are in series (Fig. 1a);
(b) *parallel systems*, in which the PM and d.c. winding fluxes are in parallel (Fig. 1b).

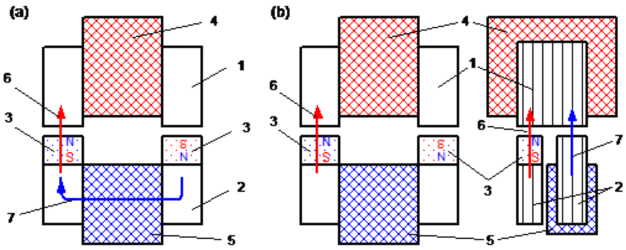

Fig. 1. Hybrid excitation systems: (a) series; (b) parallel. 1 – stator, 2 – rotor, 3 – PM, 4 – stator (armature) winding, 5 – field excitation winding, 6 – PM flux, 7 – field excitation winding flux.

An example of *series excitation system* is shown in Fig. 2a [14] and an example of *parallel excitation system* is shown in Fig.2b [18]. In the second case, the synchronous machine has a two part rotor: wound field part and PM field part [18]. Magnetic circuits of wound field part and PM part are independent of each other. The flux produced by the field current does not pass the PM because it has a large reluctance. The PM-field part is smaller than the wound-field part because the d.c. winding requires strong MMF to produce similar flux as high energy PMs.

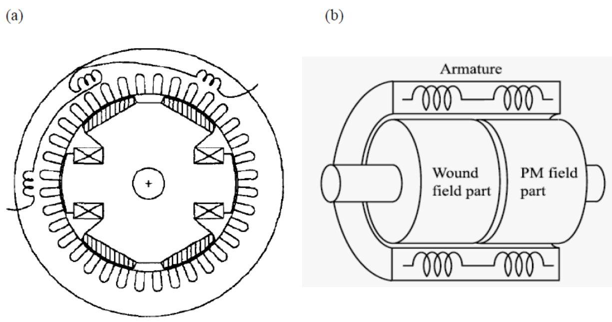

Fig. 2. Examples of hybrid excitation systems: (a) series system [14]; (b) parallel system consisting of a two-part rotor [18].

Hybrid excitation systems shown in Fig. 2. require slip rings and brushes or brushless exciters. Brushless exciters are similar to those for standard synchronous machines, i.e., the three-phase armature and rotating rectifier is on the rotor and the field excitation system of the exciter is stationary.

Hybrid field excitation systems can also be classified with respect to the geometry of the magnetic circuit, i.e.:

(a) systems with *variable reluctance* of the magnetic circuit;
(b) systems with *magnetic flux diverters*;
(c) systems with *adjustable active air gap area*.

J. F. Gieras is with Hamilton Sundstrand Aerospace, Applied Research Electrical Engineering, 4747 Harrison Avenue, Rockford, IL 61125 USA, phone: +1 (815) 226-6016, e-mail: jacek.gieras@hs.utc.com and Department of Electrical Engineering, University of Technology and Life Sciences, Al. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland, phone: +48 (52) 340-8460, e-mail: jacek.gieras@utp.edu.pl

Most field excitation systems with variable reluctance belong to the group of series systems and nearly all systems with magnetic flux diverters belong to the group of parallel systems. In systems with adjustable air gap area, the PM rotor is axially displaced with respect to the stator [12,14].

III. FIELD EXCITATION SYSTEMS WITH STATIONARY DC COIL

To eliminate slip rings and brushes, the d.c. excitation winding can be placed on the stator as shown in Figs 3 [16] and 4 [21], or in the bearing covers as shown in Fig. 5 [2].

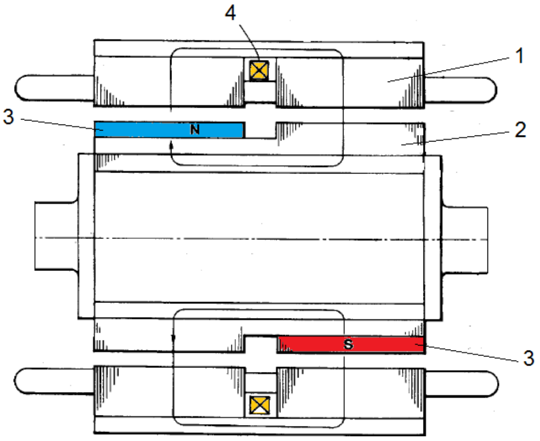

Fig 3. PM synchronous machine with d.c. field excitation winding on the stator. 1 - stator core, 2 - rotor core, 3 - PM, 4 - d.c. field winding [16].

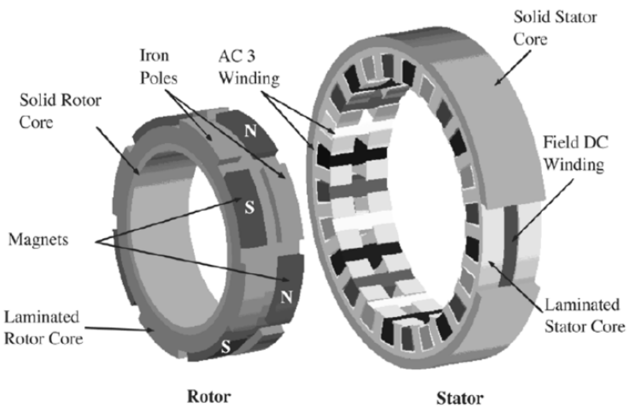

Fig. 4. 3D image of a PM brushless excitation system with d.c. field winding on the stator [21].

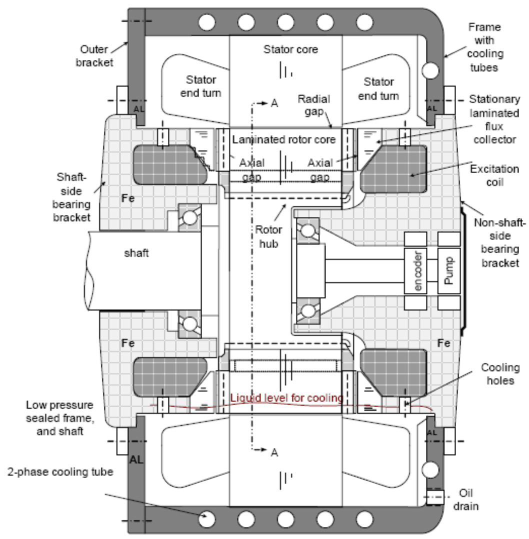

Fig. 5. Interior PM synchronous machine with additional stationary field excitation windings. Rotor PMs are not visible [2].

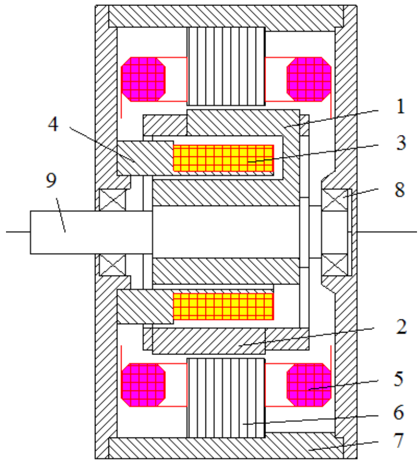

Fig. 6. PM hybrid synchronous machine with claw type rotor proposed at the University of Hong Kong [5]. 1 - North pole, 2 - South pole, 3 - d.c. field excitation winding, 4 - field winding holder, 5 - stator a.c. winding, 6 - stator core, 7 - frame (housing), 8 - bearing, 9 - shaft.

The machine shown in Fig. 4 [21] is exactly the same as that patented by T. Mizuno (Fig. 3) [16]. A similar hybrid PM as that shown in Fig. 5 [2] has been investigated at the University of Hong Kong (Fig. 6) [5].

The stationary d.c. field excitation winding increases the size and mass of the machine, contributes to the temperature increase, reduces the overall efficiency, and increases the leakage inductance of the stator a.c. winding.

IV. FIELD EXCITATION SYSTEMS WITH VARIABLE RELUCTANCE OF THE STATOR CORE

The method of regulation of a PM synchronous generator output voltage by *changing the reluctance of the stator* core has been proposed in Soviet Russia by A.I. Bertinov in 1951 [4,22]. The implementation of this method into product line has been done by A.I. Bertinov, V.G. Andreev and S.R. Mizurniy [4]. The change in reluctance for the magnetic flux has been accomplished by control of the d.c. current in the field excitation winding placed on the stator yoke. The stator d.c. field winding is located in the same slots as the a.c. armature winding, as shown in Fig. 7. By changing the d.c. current in the stator magnetizing winding (also called the d.c. *control current*), the magnetic field intensity in the stator yoke is also changed and the reluctance of the yoke can be adjusted to obtain the desired generator output voltage.

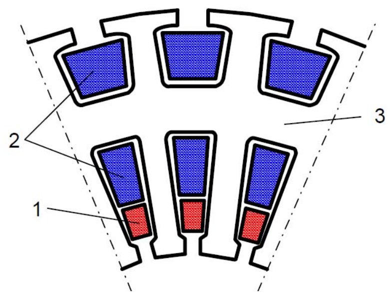

Fig. 7. Stator with toroidal d.c. winding for magnetizing the armature yoke according to A.I. Bertinov [4]: 1 – stator (armature) winding, 2 – d.c. winding field excitation winding, 3 – armature yoke. This machine has inner rotor and outer stator.

A change in the current of the d.c. excitation winding causes a change in the d.c. component of the magnetic field intensity in the armature yoke. Consequently, the magnetic permeability and reluctance of the core are functions of the d.c. excitation flux.

The MMF of the d.c. field excitation winding is usually small, because the magnetic flux produced by this winding goes only through the ferromagnetic core (no air gaps). Consequently, the required d.c. excitation power is also small. Since the d.c. flux does not penetrate through air gaps, the inductance of the d.c. field excitation winding is large.

The machine shown in Fig. 7 belongs to the group of machines with hybrid *series excitation systems*, because the d.c. magnetic flux increases or decreases the reluctance of the armature core for the PM flux.

Similar to Bertinov's invention, R. Shervington's generator (1994) [20] operates also on the principle of saturated magnetic circuit of the stator. Bertinov's generator has additional slots for d.c. *control winding* which saturates the stator yoke, while Shervington's generator uses 1/3 of existing stator slots to accommodate the d.c. control winding C1C2 (Fig. 8). Ferromagnetic slot closers (wedges) for the control winding are recommended to intensify the effect of the voltage regulation.

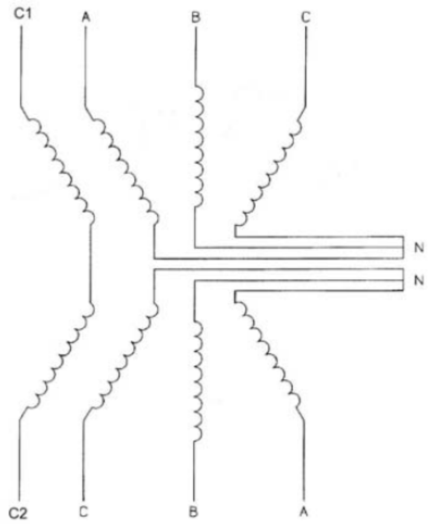

Fig. 8. Winding diagram of 3-phase generator according to [20]: ABC - terminals of armature winding, C1C2 - terminals of control winding.

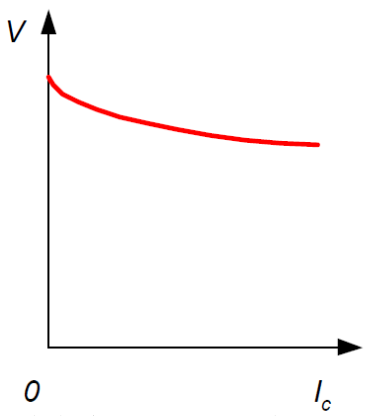

Fig. 9. Output terminal voltage V versus control current I_c of PM brushless generators with variable reluctance of the armature core.

As the d.c. control current increases, the magnetic permeability of the stator yoke decreases, so that the reluctance of the yoke for the magnetic flux increases. Increased reluctance of the yoke means that the leakage magnetic flux increases and the main (useful) magnetic flux decreases which in turn slightly reduces the magnetic flux density in the air gap, and consequently the EMF. As a result, the generator output voltage decreases with the increase in the d.c. control current (Fig. 9).

Both Bertinov and Shervington's 3-phase generators allow for voltage regulation in the range of 10 to 20%. For single phase configuration, Shervington's generator may reduce the output voltage up to 45%. The advantage of both Bertinov and Shervington's generator is that the voltage-control current characteristics are approximately linear (Fig. 9).

Bertinov's generator require more iron for the stator to accommodate the control winding. In Shervington's generator there is less room in slots for the armature winding because part of slots are occupied by the d.c. control winding.

The drawback of these generators is the reduction of the output terminal voltage with the control current (see attached slide). This may not be desired in the case of loss of control current (failure mode) because a high d.c .control current is required at no load to keep the output voltage at the rated level.

V. Field Excitation Systems with Magnetic Flux Diverters

A d.c. field excitation coils wound on an additional stator ferromagnetic yoke can effectively divert the portion of the PM magnetic flux and regulate the magnetic flux linked with the a.c. armature winding. In this case, the machine has a *parallel hybrid excitation system*. Such a synchronous generator according to invention [7] is schematically shown in Fig. 10.

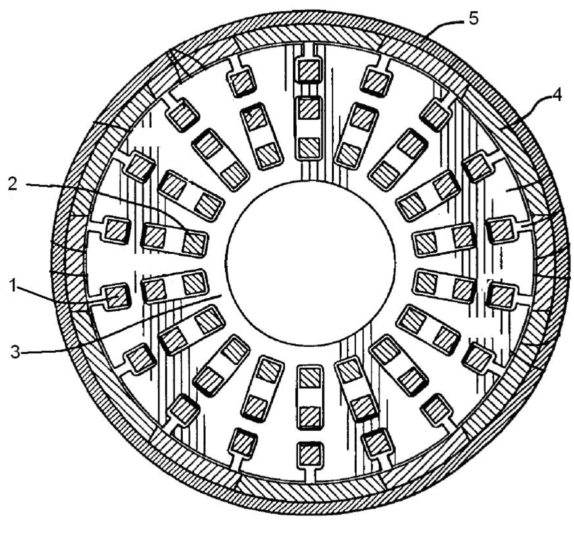

Fig. 10. Cross section of a voltage regulated generator according to invention [6,7]: 1 – three-phase armature winding, 2 – d.c. control winding, 3 – magnetic flux diverter, 4 - PM rotor, 5 - ferromagnetic yoke. This machine has inner stator and outer rotor.

The outer rotor has surface PMs magnetized radially. The inner stator has two yokes and two toroidal windings (Gramme windings). Both toroidal windings are located in slots and wound around yokes. The outer winding is the armature winding, usually a three-phase winding. The inner winding is the d.c. *control winding* used for magnetizing the inner yoke. The magnetic flux excited by outer rotor PMs penetrates through the air gap to the stator core. The stator outer and inner yokes create return paths for the magnetic flux.

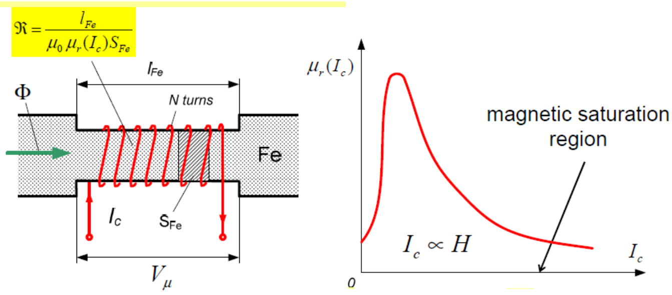

Fig. 11. The effect of control current I_c on the relative magnetic permeability and reluctance of a flux diverter.

The magnetic flux is inversely proportional to the reluctance R of the ferromagnetic core, i.e.,

$$\Phi = \frac{V_\mu}{R} = V_\mu \frac{\mu_0 \mu_r(I_c) S_{Fe}}{l_{Fe}} \qquad (1)$$

where V_μ is the magnetic voltage drop, $\mu_0 = 0.4\pi \times 10^{-6}$ H/m is the magnetic permeability of free space, $\mu_r(I_c)$ is the relative magnetic permeability of the flux diverter dependent on the control current I_c, S_{Fe} is the cross section area of the flux diverter and l_{Fe} is the length of the flux diverter (Fig. 11). The relative magnetic permeability is a function of the magnetic flux intensity. The magnetic field intensity is proportional to the current in the coil. Thus, the relative magnetic permeability varies with the current I_c.

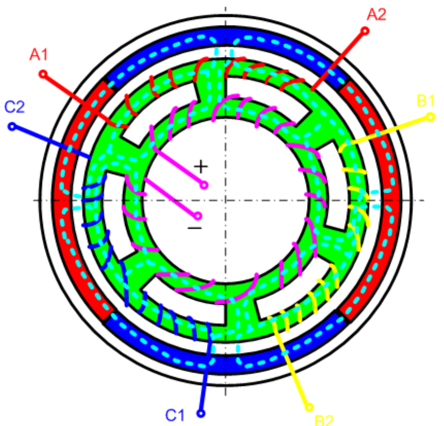

Fig. 12. Magnetic flux distribution in the machine shown in Fig. 10 for low or zero value of the d.c. winding control current.

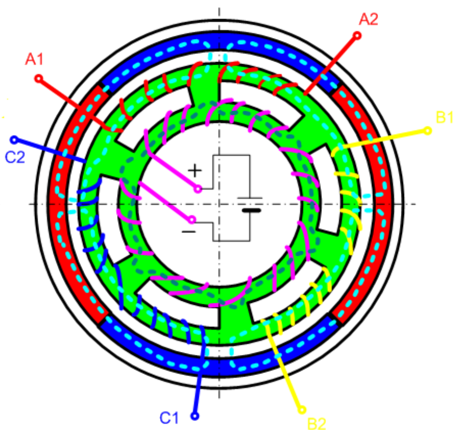

Fig. 13. Magnetic flux distribution in the machine shown in Fig. 10 for high value of the d.c. winding control current.

If the magnetic permeability of the inner stator yoke is high (low d.c. control current), a large portion of the magnetic flux goes through the inner yoke as shown in Fig. 12. The magnetic flux that excites the EMF in the armature winding depends on how much of the magnetic flux goes through the inner yoke, i.e., through the magnetic flux diverter. If the diverter flux is comparable with or higher than that in the outer yoke, the induced EMF in the armature winding is low. If the magnetic permeability of the inner stator yoke is low (high d.c. control current), almost total magnetic flux goes through the outer yoke as shown in Fig 13. Hence, the induced EMF in the armature winding is high.

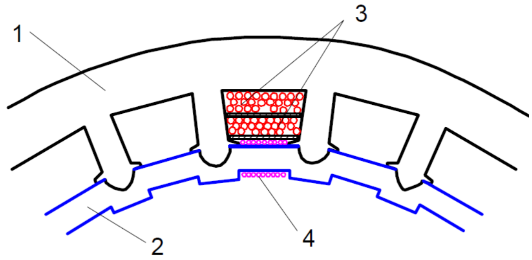

Fig. 14. Stator of the PM synchronous machine with magnetic flux regulation according to invention [9,10,11]: 1 – outer stator core with yoke and teeth, 2 – inner stator core (magnetic flux diverter), 3 – double layer armature winding, 4 – control winding. The machine has outer stator and inner rotor.

The machine according to the author's invention [9,10] operates also on the principle of magnetic saturation of the portion of the stator core with the d.c. control winding, similar to the machine shown in Figs 10, 12 and 13. The construction of the stator according to invention [9,10] is shown in Fig. 14. The stator core has a magnetic flux diverter and two windings: a.c. armature winding and control winding. The control winding can be wound with round conductor or foil (ribbon).

The reluctance of a ferromagnetic material is inversely proportional to the magnetic permeability. At zero control current $I_c = 0$, the reluctance of the magnetic shunt is low because its magnetic permeability is high. Almost total air gap magnetic flux $\Phi_g \approx \Phi_{sh}$ (produced by PMs) goes through the slot wedges (Fig. 15). The EMF induced in the a.c. stator winding is almost zero, because the magnetic flux linked with the stator winding is very small.

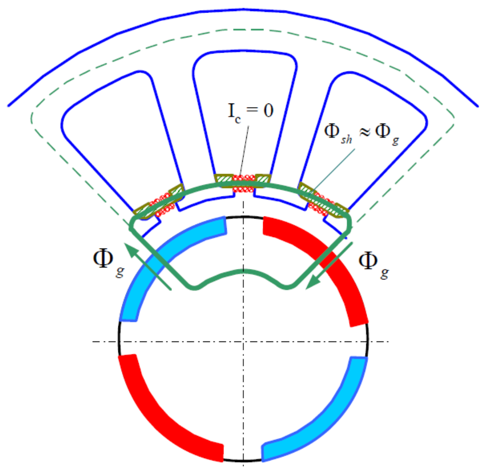

Fig. 15. Magnetic flux path in the case of zero control current $I_c = 0$, $\Phi_{sh} \approx \Phi_g$.

When the control current is greater than zero, i.e., $I_c > 0$, slot wedges partially saturate, their magnetic permeability decreases, reluctance increases and only portion of the magnetic flux Φ_{sh} is shunted by the slot wedges (Fig. 16). The magnetic flux linked with the stator a.c. winding increases, so does the EMF induced in the stator winding.

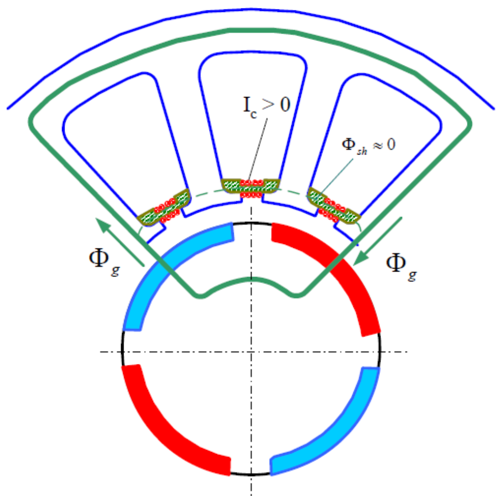

Fig. 16. Magnetic flux path in the case of saturated slot wedges, $I_c > 0$, $\Phi_{sh} \approx 0$.

Further increase in the control current reduces further the slot wedge reluctance and its relative magnetic permeability is close to unity. Fully saturated slot wedges behave as free space. Almost the whole air gap magnetic flux Φ_g excited by the rotor PMs penetrates through the stator teeth and yoke and excites maximum EMF in the stator winding.

In order to obtain analytical equations describing the machine performance, the magnetization curve $B(H)$ of the stator ferromagnetic core needs to be described analytically. To avoid complex mathematics, the magnetization curve is to be expressed with the aid of a simple equation. For analysis of the machine shown in Fig. 14 an approximation of magnetization curve proposed by L.R. Neyman has been used [19], i.e.,

$$B = KH^{\frac{1}{n}} \qquad \text{or} \qquad H = \frac{1}{K^n} B^n \qquad (2)$$

For Hyperco 50 cobalt alloy the constant K = 1.52 $(\Omega\text{s/m})^n$ and $n \approx 24$. For M19 silicon steel K = 0.85 and n = 12. Parameters of the generator are sensitive to the magnetization curves of the core and flux diverter, so that any approximation error can lead to discrepancy of the calculated and measured performance characteristics. Polynomial approximation of the magnetization curve introduce fewer errors; however, more complex equations make the analysis intricate. With the aid of Ampere's circuital law and eqn (2), the control current can be expressed as a function of the magnetic flux density B and number N_{csl} of control turns per slot, i.e.,

$$I_c = \frac{1}{K^n} B^n \frac{l_{sl}}{N_{csl}} \qquad (3)$$

where l_{sl} is the length of the magnetic flux path around stator slot for control coil flux and B is the magnetic flux density inside the flux diverter (inner yoke).

The rotor magnetic flux can induce some a.c. voltage in the control winding. This voltage can be cancelled by series connection of the same terminals, i.e. beginning with beginning and end with end of neighboring shunt coils. Such a connection can be done only in the case of d.c. control current.

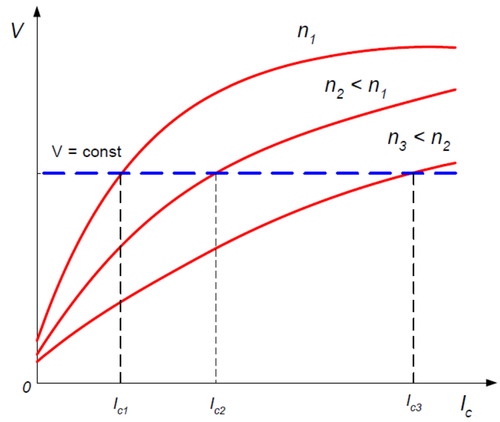

Fig. 17. Regulation characteristics $V = f(I_c)$ for three speeds n_1, $n_2 < n_1$ and $n_3 < n_2$.

The shape of the *terminal voltage – control current* $V = f(I_c)$ regulation characteristic is exactly as desired to meet aircraft generator voltage regulation requirements (Fig. 17). The smallest output voltage is at zero control current and maximum output voltage is at maximum control current. Under failure of control circuit, the terminal voltage of the generator immediately drops to its minimum value (close to zero). To keep constant output voltage, the control current is varied as shown in Fig, 17, e.g., if the speed decreases from n_1 to n_3, the current must be increased from I_{c1} to I_{c3} to increase the reluctance of wedges (flux diverters) and increase the magnetic linkage flux.

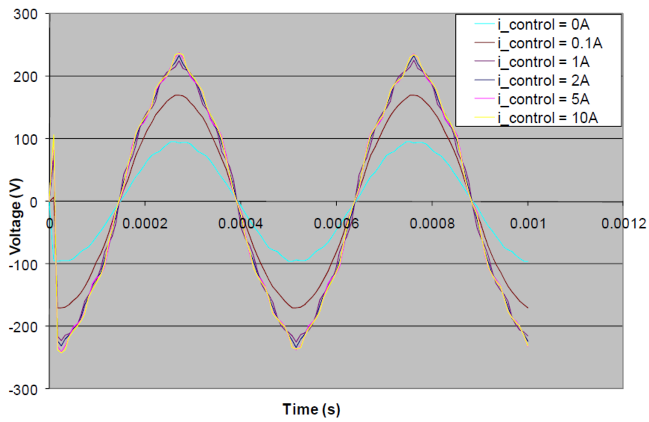

Fig. 18. EMF waveforms as functions of control current for constant speed as obtained from the 2D FEM analysis.

Thus, the regulation characteristic is similar to that of the machine according to invention [7]. The waveforms of EMF as functions of control current I_c for constant speed n = constant are shown in Fig. 18. Owing to nonlinearity of the magnetic circuit [12], the EMF is a nonlinear function of the control current I_c.

The proposed method of magnetic flux shunting [9,10,11] does not require manufacturing of a special magnetic circuit as in the case PM generators with toroidal windings [6,7]. The machine [9,10,11] has a typical construction, i.e., *outer stator* and *inner rotor*.

The simplest method of manufacturing is to make separately the outer stator (yoke and teeth) with three-phase armature winding and the inner yoke with control winding. A standard stator of a three-phase machine can also be used and adjusted to PM brushless machine with magnetic flux regulation capability. The outer stator has a typical double-layer winding and slot insulation system, while the inner stator is recommended to have insulation system made by powder coating technique.

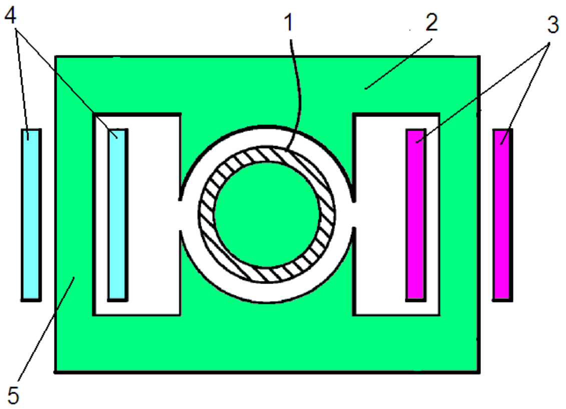

Fig. 19. Single-phase PM machine with magnetic flux regulation according to [11]. 1 – PM rotor, 2 – stator ferromagnetic core, 3 – single-phase armature winding, 4 – control winding, 5 – magnetic flux diverter.

Fig. 19 shows a simple single-phase PM machine with magnetic flux regulation [11]. This machine has only two poles, in which a part of the magnetic circuit is used as a magnetic flux diverter. The minimum linkage magnetic flux (rotor PM flux coupled with the armature winding) is at zero control current $I_c = 0$, i.e., when magnetic flux diverter is unsaturated. At $I_c > 0$, the magnetic flux diverter saturates, its reluctance for the magnetic flux increases and more rotor PM flux is linked with the armature winding. The saturation of the magnetic flux diverter has been explained in Fig. 11.

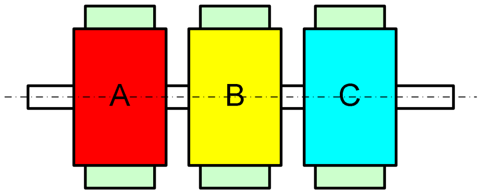

Fig. 20. Assembly of a three-phase PM machine with magnetic flux regulation according to [11] using three the same single-phase machines shown in Fig. 19.

A three phase machine can be built using three separate single-phase stators and three rotors on the same shaft [11], as shown in Fi. 20.

VI. Machines with Split Permanent Magnet Rotor

These PM generators with hybrid excitation systems belong to the group of machines with adjustable active air gap area.

The field excitation flux of a PM brushless machine can be controlled mechanically [15] or hydraulically[13] by moving axially split PM rotor assembly. Fig. 21 shows a PM brushless machine with a split rotor, in which lubricating oil is used to pressurize the rotor shaft. Magnets are forced hydraulically out of the stator stack in the axial direction. This effectively reduces the active air gap area, which reduces the magnetic flux linked with the stator and consequently reduces the EMF.

A servo-valve can be used to regulate the oil pressure in the shaft. As the pressure is increased, the rotor assembly is axially pushed out of the stator stack. As the oil pressure is decreased, the magnetic force pulls the rotor assembly back into position.

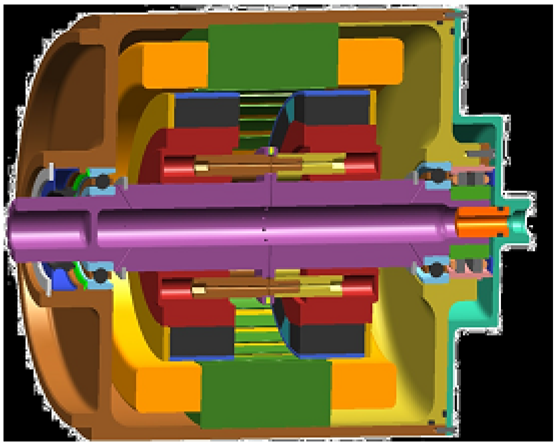

Fig. 21. PM brushless machine with split PM rotor assembly and hydraulic regulation of magnetic flux by axial movement of PMs [13].

VII. Conclusions

A variety of PM synchronous generators with hybrid field excitation systems and terminal voltage regulation capability have been discussed. The terminal voltage is controlled by variation of d.c. current in the so called *control winding*. In *series hybrid excitation systems* the output terminal voltage at constant speed decreases with the control current (Fig. 9). In *parallel hybrid excitation systems* (with magnetic *flux diverters*) the output terminal voltage at constant speed increases with the increase in control current (Fig. 17). The main role of PM synchronous generators with hybrid excitation systems is to *keep constant voltage at variable speed* of the prime mover (Fig. 17). It is especially important in synchronous generators for aircraft, automobiles, wind turbines, and microturbines. Additional control winding increases both the volume envelope and mass of the generator.

VIII. References

[1] Y. Amara, J. Lucidarme, M. Gabsi, M. Lecrivain, A.H.B. Ahmed, and A. Akemakou, "A new topology of a hybrid synchronous machine," *IEEE Trans. on IA*, vol. 37, 2001, No 5, pp. 1273 - 1281.

[2] *Annual Progress Report for the Power Electronics and Electric Machinery Program*, ORNL, Oak Ridge, 2005.

[3] M. Aydin, S. Huang, and T.A.Lipo, "Performance evaluation of an axial flux consequent pole PM motor using finite element analysis," *Int. Electr. Machines and Drives Conf. IEMDC'03*, Madison, WI, 2003, pp. 1682 – 1687.

[4] V.A. Balagurov, F.F. Galteev, and A.N. Larionov, *Permanent magnet electric machines* (in Russian), Moscow, Energia, 1964.

[5] C.C. Chan, K.T. Chau, J.Z. Jiang, W. Xia, M. Zhu, and R. Zhang, "Novel permanent magnet motor drives for electric vehicles,", *IEEE Trans. on IE*, vo. 43, 1996, No. 2, pp. 331-339.

[6] K.A. Dooley, "Architecture for electric machine," U.S. Patent 6,965,183, November 15, 2005.

[7] K.A. Dooley, "Saturation control of electric machine," U.S. Patent 7999431, August 16, 2011.

[8] J.F. Gieras, *Permanent magnet motors technology: design and applications*, 3rd edition, Taylor & Francis, Boca Raton, London, New York, 2010.

[9] J.F. Gieras and G.I. Rozman, "Permanent magnet electric generator with variable magnet flux excitation," U.S. Patent 7777384, August 17, 2010.

[10] J.F. Gieras and G.I. Rozman, "Permanent magnet electric generator with variable magnet flux excitation," US Patent 7859231, December 28, 2010.

[11] J.F. Gieras, G.I. Rozman, "Voltage regulated permanent magnet generator," US Patent 8085003, December 27, 2011.

[12] J.F. Gieras, "Analytical method of calculating the electromagnetic field and power losses in ferromagnetic halfspace taking into account saturation and hysteresis," *Proceedings IEE* (UK), vol. 124, 1977, No. 11, pp. 1098-1104.

[13] R. A. Himmelmann, M.F. Shahamat, and D. Halsey, "Permanent magnet dynamoelectric machine with axially displaceable permanent magnet rotor assembly," US Patent Publication 2007/0241628, October 18, 2007.

[14] X. Luo, and T.A. Lipo, "A synchronous/permanent magnet hybrid a.c. machine," *IEEE IAS Meeting*, 1999, pp. 19-21.

[15] F.B. Mc Carthy, "Permanent magnet dynamoelectric machine," US Patent 4578609, March 25, 1986.

[16] T. Mizuno, "Hybrid excitation type permanent magnet machine," US Patent 5682073, October 28, 1997.

[17] S. Morimoto, Y. Takeda, T. Hirasa, and K. Taniguchi, "Expansion of operating limits for permanent magnet motor by current vector control considering inverter capacity," *IEEE Trans. on IA*, vol. 26, 1990, No. 5, pp. 866 – 871.

[18] N. Naoe and T. Fukami, T.: "Trial production of a hybrid excitation type synchronous machine," *Int. Electr. Machines and Drives Conf. IEMDC'01*, Boston, MA, 2001, pp. 545 – 547.

[19] L.R. Neyman, *Skin effect in ferromagnetic bodies* (in Russian). Energia, Moscow, 1949.

[20] R. Shervington, H. Mansir, and D.M. Kramer, "Quasi-regulated permanent magnet generator, US Patent 5714823, February 3, 1998.

[21] J.A. Tapia, F. Leonardi, and T.A. Lipo, "Consequent-pole permanent-magnet machine with extended field weakening capability," *IEEE Trans. on IA*, vol. 39, 2003, No 6, pp. 1704 – 1709.

[22] Z. Zycki, "Development of concepts of permanent magnet electric machines – structure, theory and applications" (in Polish), 33rd Symposium of Electrical Machines SME'97, Poznan, Poland, 1997, pp. 1 – 25.

IX. BIOGRAPHY

Jacek F. Gieras (M'83–SM'87–F'02) graduated in 1971 from the Technical University of Lodz, Poland, with distinction. He received his PhD degree in Electrical Engineering (Electrical Machines) in 1975 and Dr habil. degree (corresponding to DSc), also in Electrical Engineering, in 1980 from the University of Technology, Poznan, Poland. His research area is Electrical Machines, Drives, Electromagnetics, Power Systems, and Railway Engineering. From 1971 to 1998 he pursued his academic career at several Universities worldwide including Poland (Technical University of Poznan and Academy of Technology and Agriculture Bydgoszcz), Canada (Queen's University, Kingston, Ontario), Jordan (Jordan University of Sciences and Technology, Irbid) and South Africa (University of Cape Town). He was also a Central Japan Railway Company Visiting Professor at the University of Tokyo (Endowed Chair in Transportation Systems Engineering), Guest Professor at Chungbuk National University, Cheongju, South Korea, and Guest Professor at University of Rome *La Sapienza*, Italy. In 1987 he was promoted to the rank of Professor (life title given by the President of the Republic of Poland). Since 1998 he has been affiliated with United Technologies Corporation, U.S.A., most recently with Hamilton Sundstrand Applied Research. In 2007 he also became Faculty Member (Full Professor) of the University of Technology and Life Sciences in Bydgoszcz, Poland.

He authored and co-authored 11 books, over 250 scientific and technical papers and holds over 60 patents and patent publications. The most important books are *Linear Induction Motors*, Oxford University Press, 1994, U.K., *Permanent Magnet Motors Technology: Design and Applications*, Marcel Dekker Inc., New York, 1996, 2nd edition 2002, 3rd edition 2010 (Taylor & Francis), *Linear Synchronous Motors: Transportation and Automation Systems*, CRC Press LLC, Boca Raton, Florida, 1999, 2nd edition 2011, *Axial Flux Permanent Magnet Brushless Machines*, Springer-Kluwer Academic Publishers, Boston-Dordrecht-London, 2004, 2nd edition 2008, *Noise of Polyphase Electric Motor*s, CRC Press - Taylor & Francis, 2005, and *Advancements in Electric Machines*, Springer, Dordrecht-London-New York, 2008.

.