VARIABLE SPEED ELECTRIC GENERATORS FOR THE DISTRIBUTED POWER SYSTEMS OF THE FUTURE?

Lucian Mihet-Popa
"POLITEHNICA" University of Timisoara
Blvd. V. Parvan nr.2, RO-300223Timisoara
mihetz@yahoo.com

Abstract. *The steady growth of electric energy needs and the environmental constraints have led to the development of renewable resources (wind and hydro) together with more distributed and flexible power systems. Active power fast control through energy storage in pump-storage power plants, power electronics for voltage control and DC power lines are all characteristics of the more flexible power systems of the future. The above trends suggest that electric generators at variable speed might be the next big step to the really flexible, intelligent, distributed, power systems of the future. The present paper reviews quite a few solutions of electric generator systems at variable speed from large (300 MW) to small (500 kW-5 MW) power per unit and from full bi-directional power flow (generator/motor) to generator only at variable speed.*
Keywords: *variable speed, bi-directional PWM converter, power systems.*

Introduction

Until not long ago the norm in electric generators was the use synchronous machines at ever higher rated power per unit because efficiency was higher. Safety (redundancy) and environmental problems have changed this norm considerably in the last decade.

The maximum power per unit tends to decrease from 1500 MVA perhaps to (300-500) MVA in the near future. Higher power per unit in today's nuclear plants (660 MW or more) will hopefully follow course to reduce the impact of any potential accident per reactor unit.

The opening of electric energy markets in USA and Western Europe, first, will inevitably diversify the energy suppliers. There will be more of them and they will be smaller. Smaller because of capital limitations and because renewable energy resources (in wind and hydro [1]) come into smaller power per unit. More over the exploitation of distributed power systems with multiple energy providers requires much more flexibility in terms of fast and reliable active and reactive power flow control.

The existing efforts towards more flexibility through high voltage dc power buses and voltage fast control take advantage of the recent progress in large power electronics. Still, the biggest barrier to flexibility is the synchronous generator's necessity to operate at a fixed (synchronous) speed.

It seems, at a first glance, a bit daring to suggest that electric energy generation at constant speed era is close to an end but that may gradually happen. The main means to this goal are again power electronics and digital control, together with the reduction of maximum power per unit to perhaps 300 MW or so. The rapid development of combined cycle gas turbines with efficiency up to 60 % will assist this goal essentially.

The recent high voltage generator concepts (power formers [4]) are read as steps in the same direction.

Are there electric generators at variable speed connected to the power grid that can substantiate the claim that their rapid extension in the near future is technologically feasible?

Fortunately the answer is yes. I mention here two representative examples:

- 0.5 – 2 MW power wind generators to the grid [2, 15, 18];
- 300 MW pump – storage hydro electric generators / motors [1]

Incidentally both make use of double fed induction machines [2, 3, and 5] with the power electronics converter serving the wound rotor to reduce the over all costs.

Also a few synchronous generators with full power electronics converters are in use [6, 14].

For wind generators bi-directional power flow is needed only for generating below and above conventional synchronous speed ($n_1 = f_1 / p_1$).
In the case of pump – storage the generator will switch to motoring for the pumping mode. Variable speed is good for pumping at maximum efficiency and in keeping the up - stream and down – stream lakes cleaner and healthier for fish life. It serves to store energy during off peak hours from the today's dominant fossil – fuel electric power plants.
Wind electric energy production is growing rapidly every year. Off shore wind farms with a few 2 MW units are already in use in quite a few places [7]. Not yet for the smaller (less than 30 MW) hydroelectric energy production that's potential exceeds the wind energy available in many regions. Due to higher speed, the energy density in these small – hydro plants is considerably larger than with wind plants and they may reduce floods, provide more drinking water supply, assist irrigation, and encourage healthy tourism.
Let me stop here the torrent of arguments in favors of electric generators at variable speed and discuss a few solutions of practical interest based on present developments worldwide.

Large and low power induction generators at variable speed

Variable speed in large power electric generators may be required for:

- Better efficiency in electric energy production for more flexibility and stability in the power system. This applies to any kind of electric power plant (fossil fuel, nuclear, hydro, wind energy);
- It generates more energy by operating on a larger speed range;
- It minimizes the audible noise when operating in light winds;
- It simplified the mechanical design and reduces mechanical stress;
- Energy pump – storage during off – peak hours.

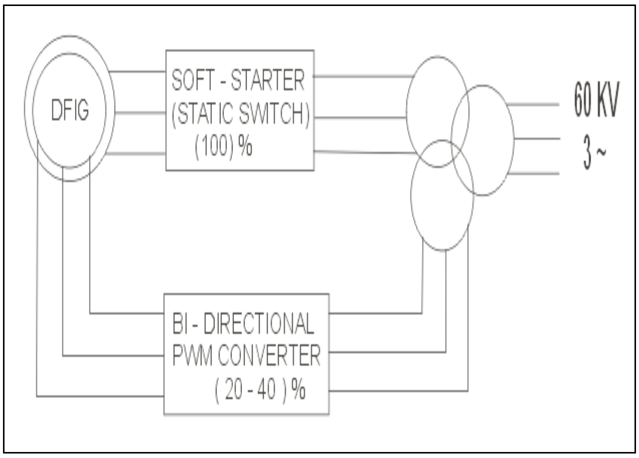
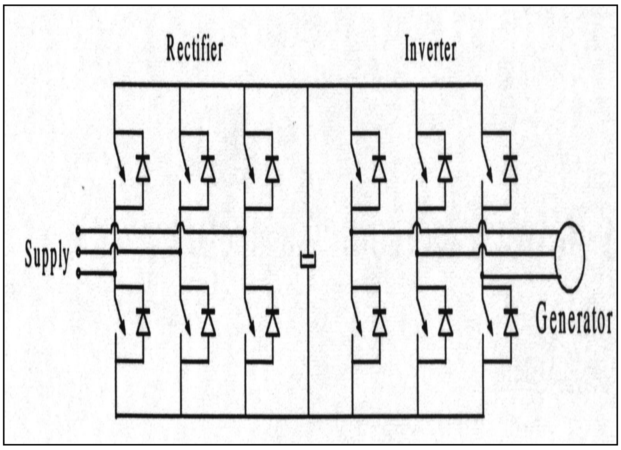


Figure. 1. The doubly fed induction generators with under – rated bi – directional power electronics converter to supply the wound rotor.

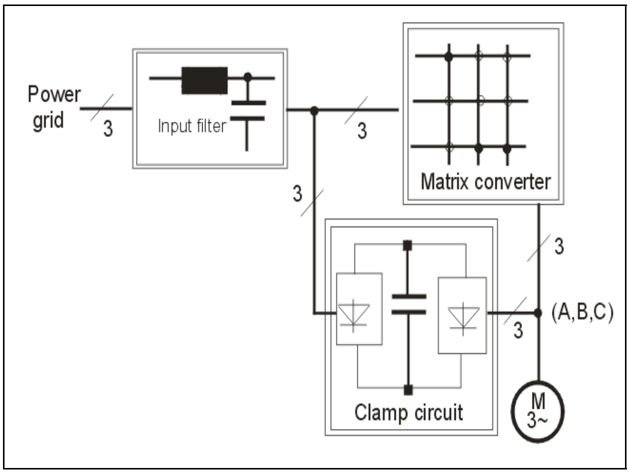
For both these scopes at large powers (up to 300 MW or even more) the doubly fed induction generator, with bi – directional under rated power electronics converter to supply its wound rotor, seems the first alternative (Figure 1)
Basically it could work as a motor and a generator both at sub and hyper synchronous speed ($n <> f_1 / p_1$). The bi – directional power converter should be able to handle this four – quadrant operation [5, 9, 10 and 16].
The rotor side converter should also handle the no load self-starting in the case of pump storage.
Synchronization is also a special issue. And so is the transition through the synchronous speed $n_1 = f_1 / p_1$.

PEC configurations of interest are:

- Back to back voltage source PWM inverters (figure 2a);
- Matrix converters (figure 2b)



a)



b)

Figure. 2. Back to back voltage source PWM converter a) and matrix converter b) for supplying the wound rotor of DFIG.

While three level large power voltage source PWM, MCT converters are available up 10 MW, the bi – directional combo has still to be implemented. The matrix converter, so promising, is still in the laboratories. A two – secondary transformer for voltage adapting is required (Figure 1).

The PEC sizing is related to speed control range. Say the maximum slip varies from zero to $\pm S_{\max}$. Then the PEC active power rating is S_{max} P_{rated}.

For a minimum power factor of $1/\sqrt{2}$ the converter kVA rating is about:

$kVA_{rating} = \sqrt{2} S_{\max} P_{rated}$ (kW)……………(1)

The steady state and transient behavior of DFIG has been thoroughly investigated mainly through digital simulations. However bi – directional operation below and above synchronous speed ($n_1 = f_1 / p_1$), machine optimization design, converter and system design are still in the incipient phase with only few practical realizations.

Self-starting for motoring may be accomplished through the rotor adequate supply with the stator first short – circuited. Once the synchronization speed is achieved ($n > f_1 / p_1 (1 - S_{\max})$) the stator short – circuit is opened, and the stator is connected to the power grid such that to limit the transients in the power system. The adequate vector or DTC control for the rotor side PEC should handle this situation elegantly and offer decoupled active and reactive power control. Concerted efforts from Academia and Industry are needed before establishing DFIG as a general variable speed generator (motor) at large and lower powers (wind and mini-hydro – plants require powers below 5 MW / unit).

Retrofitting large and medium power synchronous generators for variable speed.

The recent development of power former (high voltage synchronous generator) may prove a bonus for retrofitting the synchronous generator for variable speed by the use of an intermediary dc power bus (Fig. 3).

A high (10 – 60 kV) generator (power former [8] or wind former [6]) seems a good configuration.

Six phase generators or generating at 100 (120) Hz or more in three – phase machines may be used to reduce the DC-link filter rating.

The speed control of the turbines is still required but their perfect synchronization is not.

Voltage control will control both the output active and reactive power to the power system through speed and, respectively field current control.

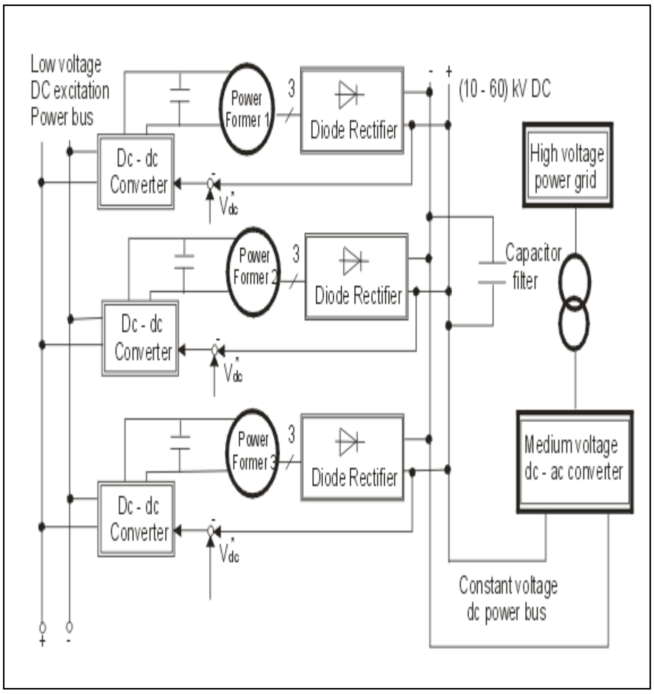


Figure. 3. Multiple synchronous generator plant with medium voltage dc power bus.

A medium voltage full rating large power converter is required. Though such a configuration exists from when long high voltage DC power ties have been built, the cost – competitiveness is still open to notable improvements.

Consequently, its immediate application is rather feasible for powers below (50 – 100) MW power plants with fast gas turbines where MCT converters are already in advanced development stages [6].

The main limitation of the scheme in Fig. 3 is that it does not allow any motoring (for pump storage). However, in many cases, this attribute is not necessary (in thermal power plants).

Low power moderate costs schemes

For powers in the 2 – 5 MW unit range, besides solutions such as those presented in paragraphs 2 and 3, lower cost configurations may be used [17, 18].

The figure 4 presents the dual-stator winding induction machine with cage rotor [11, 12 and 13], in a different utilization.

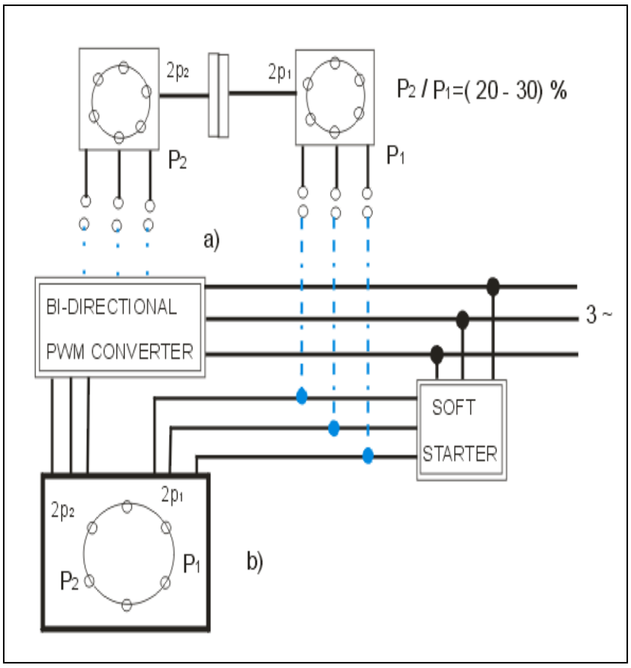


Figure. 4. Dual machine a) and dual stator winding induction generator (IG), with cage rotor b).

The two windings have $p_1, p_2 (p_1 \neq p_2)$ pole pairs and power ratings in the ratio of $P_2 / P_1 = 0.2 - 0.3$.

The second stator winding is supplied by a bi – directional PEC while the stator is connected to the power grid through a soft - starter.

The PEC machine side works both for speeds above synchronous speed $n_1 = f_1 / p_1$ to assist the main machine side, and, alone, below 25 – 30 % of rated power at lower speed (down to (70 – 80) % of rated speed) (Figure 4). Also the PEC machine could be used as a starter. As expected the PEC machine side could be used as a drive for the IG or fast breaking from any speed (figure 5).

This solution brings notable flexibility with a very rugged configuration at moderate costs. It could work also in the motoring mode with both stator windings (machines) on, but only in the sub-synchronous $(n < f_1 / p_1)$ mode.

The soft starting of the large power machine side (P_2) will reduce power grid connection transients. Motoring with the converter fed machine side is a built in capability.

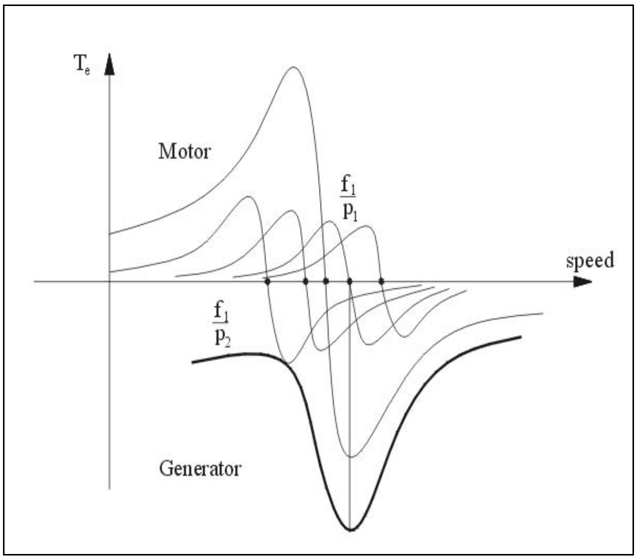


Figure. 5. Operation characteristic of dual winding induction generator (DW-IG).

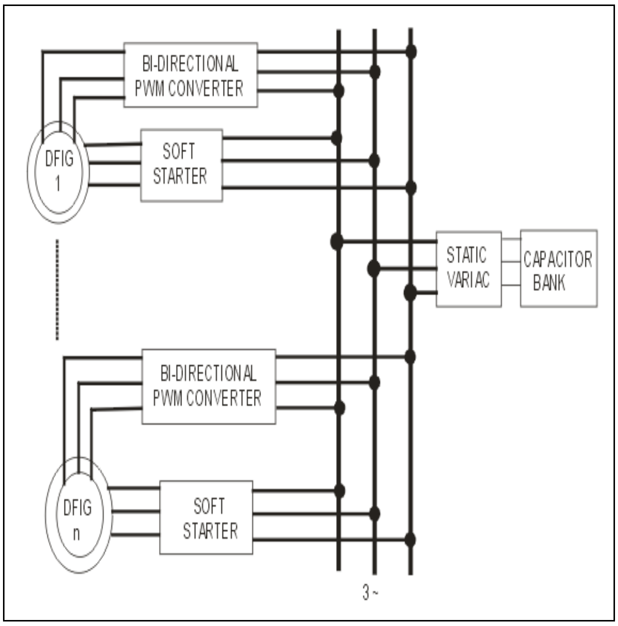


Figure. 6. Doubly fed induction generator (DFIG) insular power system with fixes constant frequency and voltage at variable speed.

An insular power system with induction generators only and a variable capacitance bank for magnetization and voltage control may also be conceived. If the frequency has to be constant the DFIG (Figure 6) is used; if not the cage rotor IG suffices.

Conclusions

The present paper investigation of selected potential solutions for variable speed electric generators has led to only three principal configurations based on the:

- Doubly – fed wound rotor induction generator (DFIG);
- Multiple synchronous generator at high voltage (power former with cable – stator winding) and diode rectifier with constant voltage dc power bus and dc – ac full power converter;
- The cage – rotor dual – stator winding induction generator for power below 5 MW (in general).

Solutions 1 and 3 make use a bi – directional, partial rating (20 – 30 %) PWM converter is implemented via back-to-back voltage source PWM inverters or by matrix converters. An important advantage of a DFIG drive is the rotor converter need only be rated for a fraction of the total output power (20-25 %) of the total generator power. The fraction is depending on the allowable sub- and super-synchronous speed range.

With the exception of the matrix converter (which is still in the laboratory stages) all the other components of the variable speed electric generators system are already available, at full power ratings.

Putting them together in distributed flexible power systems is still to be done and requires important technological & policy-making efforts. Will they be made in the near feature?

The recent mandatory energy delivery interruptions in California should be read as a severe warning sign, in the sense that flexible long – term electrical energy production, distribution and conservation plans are necessary.

References

[1] K. Kudo, “Japanese experience with a converter – feed variable speed pump – storage system, Hydropower and Dams”, No. 3, 1994, pp. 67 – 71.

[2] A. Pfeiffer, V.A. Tech ELIN, "Variable speed motor / generators", 1999, pp. 1 – 11, Penzinger St. 76, A – 1141, Vienna P.O.B.5.

[3] L. Schreier, M. Chomat, J. Bendel, "Working regions of adjustable – speed units with doubly – fed machines", Record of IEEE-IEMDC Conf, Seattle, 1999, pp. 457 – 459.

[4] L.H. Hansen, "Generator concepts and their progress", Seminar on *Control concepts of wind turbines,* University of Aalborg, Aalborg-Denmark, October 23, 2000.

[5] J.L. Kristensen, "Vestas wind system with double fed induction generator based wind turbines", Seminar on *Control concepts of wind turbines,* University of Aalborg, Aalborg-Denmark, October 23rd , 2000.

[6] B. Wortmann and L.H. Hansen, "Multipole Generator Wind Energy Converter without Gearbox and with Variable Speed", 2000, NEG Micon A / S.Randers, Denmark.

[7] P. Sorensen, B.Bak-Jensen, J. Kristiansen, A.D. Hansen, "Power plant characteristics of wind farms", Special topic conference - Wind power for the 21 st Century, Kassel, Germany, September 2000.

[8] Siegfrid Heier, "Grid Integration of Wind Energy Conversion Systems", book, Kassel University 1998, John Wiley & Sons.

[9] M.N. Escander and M.T. El-Hagry, "Optimal performance of double output induction generator used in WECS", Electric machines and power systems, Vol. 25, No 10, pp. 1035-1046, Dec. 1997;

[10] I. Cadirci, M. Ermis, "Performance Evaluation of a Wind Driven DOIG Using a Hybrid Model", IEEE Transaction on Energy Conversion, June 1998, Vol. 13, No 2, pp. 148 - 155;

[11] O. Ojo and I.E. Davidson, "PWM-VSI Inverter-Assisted Stand-Alone Dual Stator Winding Induction Generator", IEEE Transaction on Industry Applications, Vol. 36, No. 6, pp. 1604 - 1610, November / December 2000;

[12] A. Munoz-Garcia and Thomas A. Lipo, "Dual Stator Winding Induction Machine Drive", IEEE Transaction on Industry Applications, 1/1998, pp. 601 - 608.

[13] I. Tamrakar and O.P. Malik, "Power Factor Correction of Induction Motors using PWM Inverter Fed Auxiliary Stator Winding", IEEE Transaction on Energy Conversion, Vol. 14, No. 3, pp. 426-433, September 1999.

[14] L.H. Hansen, P. Sorensen, U.S. Paulsen, "Variable Speed Wind Turbine using Full Conversion", Contribution to the NORpie Conference in Aalborg-Denmark, pp. 115-119, June 13th to 16th, 2000.

[15] Lucian Mihet-Popa, F. Blaabjerg and I. Boldea, "Wind Turbine Generator Modeling and Simulation where Rotational Speed is the Controlled Variable", IEEE-IAS Transactions on Energy Conversion, January / February 2004, Vol. 40, No. 1, pp. 3-10.

[16] Lucian Mihet-Popa and Ion Boldea, "Variable speed wind turbines using induction generator connected to the grid: digital simulation versus test results", IEEE – the 9th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2004, May 20-21, Poiana Brasov, Vol. 2, pp. 286-294.

[17] Lucian Mihet-Popa**, "**Variable Speed Wind Turbines using Cage Rotor Induction Generators Connected to the Grid**",** Proceedings of the 12th Romanian National Conference of Electrical Drives (CNAE), Cluj-Napoca, September 23rd-25th, 2004, Cluj-Napoca, pp. 261-266;

[18] Lucian Mihet-Popa**, "**Wind Turbines using Induction Generators connected to the grid**",** Ph. D. Thesis, POLITEHNICA University of Timisoara, October 2003.