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Induction Generators for Small Wind Energy Systems

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Introduction

Background

The use of induction generators can be traced back to the beginning of the 20th century until they were almost disappeared in the 1960s [1]. The dramatic increase in gas prices during the 1970s, created the favorable situation for the revival of the induction generator. With such high energy costs, rational use and conservation implemented by many processes of heat recovery and other similar forms became important goals. By the end of the 1980s, wider distribution of population over the planet, with improved transportation and communication that enabled people to move away from large urban concentrations, and growing concerns with the environment led to demand by many isolated communities for their own power plants. The general consciousness of finite and limited sources of energy on earth and international disputes over the environment, global safety, and the quality of life have created an opportunity for new, more efficient, less polluting power plants with advanced technologies of control, robustness, and modularity. In this new millennium of 21st century, the induction generator, with its lower maintenance demands and simplified controls, appears to be a good solution for such applications [1]. For its simplicity, robustness, and small size per generated kW, the induction generator is favored for small hydro and wind power plants. More recently, with the widespread use of power electronics, computers and electronic microcontrollers, it has become easier to use these generators with increased efficiency for the power generation up to 500 kW. The induction generator is always associated with alternative sources of energy as for the small power plants, it has a great economic appeal. Standing alone, its maximum power does not go much beyond 15 kW. Alternatively, if an induction generator is connected to the grid or to other sources or storage, it can easily approach 100 kW [1]. Very specialized and custom-made wound-rotor schemes enable even higher power. More recently, power electronics and microcontroller technologies have given a decisive boost to induction generators for wind energy generation because they enable very advanced and inexpensive types of control, new techniques of reactive power supplements, and asynchronous injection of power into the grid.

Generator Selection for Wind Energy

An important step for installation of wind energy system is to select the turbine rating, the generator, and the distribution system. In general, the output characteristics of the wind turbine power do not follow exactly those of the generator power; so they have to be matched in the most reasonable way possible. Based on the maximum speed expected for the turbine and taking into account the cubic relationship between the wind speed and the generated power, the designer must select the generator and the gearbox so as to match these limits. The most sensitive point here is the correct selection of the rated speed for the generator. If it is too low, the high speed of the primary source wind will be wasted; if it is too high, the power factor will be harmed. The characteristics of the commercially available turbines and generators must be matched to the requirements of the project with regard to cost, efficiency, and maximum generated power in an iterative design process [1].

Several types of generators can be coupled to the rotating wind power turbines: dc and ac types, parallel and compound dc generators, with permanent magnets or electrical field excitation, synchronous or non-synchronous, and, especially, induction generators. The dc machines are not usually employed because of their high cost, bulky size, and maintenance needs. The right choice of generator depends on a wide range of factors related to the primary source, the type of load, and the speed of the turbine, among others [1]. Besides, systems differ with respect to their applications, whether they are stand-alone or connected to the grid, their degree of interruptibility, and the quality and cost of their output. Because of the way it works as a motor or generator, the possibility of variable speed operation, and its low cost compared to other generators, the induction machine offers advantages for rotating power plants, like the wind power, in both standalone and interconnected applications [1].

Induction Generator

Typically, small renewable energy power plants rely mostly on induction machines, because they are widely and commercially available and very inexpensive. It is also very easy to operate them in parallel with large power systems, because the utility grid controls voltage and frequency while static and reactive compensating capacitors can be used for correction of the power factor and harmonic reduction [2], [4], [5]. Although the induction generator is mostly suitable for hydro and wind power plants, it can be efficiently used with prime movers driven by diesel, biogas, natural gas, gasoline and alcohol motors. Induction generators have outstanding operation as either motor or generator; they have very robust construction features, providing natural protection against short-circuits, and have the lowest cost with respect to other generators. Abrupt speed changes due to load or primary source changes, as usually expected in small power plants, are easily absorbed by its solid rotor, and any current surge is damped by the magnetization path of its iron core without fear of demagnetization, as opposed to permanent magnet based generators [2], [6].

The induction generator has the very same construction as the induction motors with some possible improvements in efficiency. There is an important operating difference; the rotor speed is faster with respect to the stator magnetic field rotation. In quantitative terms [2], if n_s is the synchronous mechanical speed in rpm at the synchronous frequency f_s in Hz, the resulting output power comes from the induced voltage proportional to the relative speed difference between the electrical synchronous rotation and the mechanical rotation within a speed slip factor range given by:

$$S = (n_s - n_r)/n_s \qquad (1)$$

where; S is the slip, n_r is the rotor speed in rpm.

Self-Excited Induction Generator

For its operation, the induction generator needs a reasonable amount of reactive power which must be fed externally to establish the magnetic field necessary to convert the mechanical power from its shaft into electrical power [1]. Therefore, the external reactive source must remain permanently connected to the stator windings responsible for the output voltage control. In interconnected applications, the synchronous grid supplies such reactive power. In stand-alone applications, the reactive power must be supplied by the load itself, or by a bank of capacitors connected across its terminals, or by an electronic inverter. When capacitors are connected to induction generator, the system is usually called a SEIG (a self-excited induction generator) [1], [2], as shown in Figure 1(a). When the shaft is rotated externally, such movement interacts with a residual magnetic field and induces a voltage across the external capacitor, resulting in a current in the parallel circuit which, in turn, reinforces the magnetic field and the system builds up an increasing excitation. Due to high cost of capacitors and maintenance needs, self-excitation of the induction generator is economically recommended only for small power plants [7], [8].

When several SEIGs operate interconnected, each induction machine requires a certain capacitance bank depending on the primary energy, the magnetization curve of the core and the instantaneous load. So, the interaction among the operational state of the primary source of energy with the induction generator, the self excitation parameters and the load, will define the overall performance of the power plant [9], [10], [11]. The performance is greatly affected by the variance of some of the parameters related to the availability of primary energy and load variations.

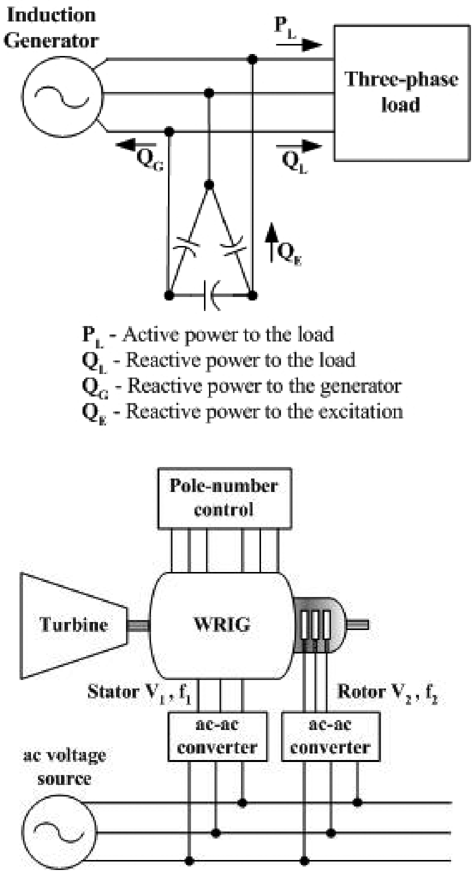

Figure 1. (a) Capacitor self-excited induction generator, (b) DFIG-overall stator and rotor parameter control

Doubly Fed Induction Generator

A very important machine, typically used for high power applications, is the doubly fed induction generator (DFIG). The DFIG is a wound rotor machine where the rotor circuit is connected to an external variable voltage and frequency source via slip rings and the stator is connected to the grid network [2], as illustrated in Figure 1(b). There is also a possibility of altering the rotor reactance by effectively modulating some inductors in series with the original rotor reactance. Adjusting the frequency of the external rotor source of current controls the speed of the doubly fed induction generator, which is usually limited to a 2:1 range. Doubly fed machines were not very popular in the past due to the maintenance required for the slip rings. More recently, with the development of new materials, powerful digital controllers and power electronics, the doubly fed induction generator became a solution in power generation for up to several hundreds of kW ratings [2]. Power converters usually make up the need for a variable frequency source for the rotor.

As it is said above, the control of doubly fed induction generators can be exerted either through the stator or rotor variables. The controllable stator variables are number of poles, voltage and frequency [2]. The rotor variables for squirrel cage rotors can be design resistance, design reactance and speed. The doubly fed induction generator is affected by the second power of the grid voltage and the controllable variables are current, voltage, frequency, and voltage phase shift with respect to the stator voltage angle. An experimental set up [2], to implement and monitor changes in the stator and rotor characteristics, is depicted in Figure 1(b). Obviously, in most applications, this setup can be simplified. If, for example, there is no interest in stator frequency or voltage changes, the stator power converter is not required in practice.

Interconnected and Stand-Alone Operation

When directly interconnected with the distribution network, an induction machine must change its speed (increased up to or above the synchronous speed). The absorbed mechanical power at the synchronous speed is right enough to withstand the mechanical friction and resistance of the air. In case the speed is increased just above the synchronous speed, a regenerative action happens, yet without supplying energy to the distribution network. This will happen only when the de-magnetizing effect current of the rotor is balanced by a stator component capable of supplying its own iron losses and, above that, supplying power to the external load. When considering interconnection with or disconnection from the electric distribution network, it should be observed that there is a rotation interval above the synchronous speed in which the efficiency is very low. This effect is caused by the fixed losses related to the low level of generated power and torque in these low speeds [12].

Another relevant aspect is the maximum rotation. At this point, disconnection from the distribution network should occur, so that a control system will act as a brake for the turbine under speed controlled operation. The disconnection should be performed for electric safety of the generator in the case of a faliure in the control brake, and for the safety of the local electric power company maintenance teams when the generator should be disconnected from the distribution network.

Connection of induction generators to the distribution network is quite simple process, as long as the interconnection and protection guidelines by the local utilities are followed. Technically, the rotor is put to rotation in the same direction in which the magnetic field is rotating, as close as possible to the synchronous speed to avoid unnecessary speed and voltage mismatches [2]. A phenomenon similar to the connection of motors or transformers to the distribution network will happen resulting in a transient exchange of active and reactive power between generator and load. The load here considered can be any ordinary electrical load or a power inverter for interconnection with the distribution network or any ac load.

The active power supplied by an induction generator to the load, similar to what happens with the synchronous generators, can be controlled by speed change which is related to controlling the mechanical primary power. For the case of stand-alone operation, the magnetizing current is to be obtained from the self-excitation process. The mechanical energy of rotation can only influence the active component of the current with no effect on the reactive component.

In the case of an induction generator in parallel with a synchronous machine, the excitation depends on the relative speed between them, so the short circuit current supplied depends on the voltage drop produced across the terminals of the synchronous generator. If the voltage across the terminals goes to zero, the steady state short circuit current is zero. The induction generator dampens oscillations, as long it does not have to run at the synchronous speed. All the load variation is followed by a speed variation and small phase displacement, much the same with the synchronous generator [2].

Wind Power Integration by Induction Generator

Integration of alternative sources of energy into the network for Distributed Generation (DG) requires small-scale power generation technologies located close to the loads served. The move toward onsite distributed power generation has been accelerated because of deregulation and restructuring of the utility industry and the viability of alternative energy sources. DG technologies can improve power quality, boost system reliability, reduce energy costs, and defray utility capital investment [2].

The integration of renewable sources of energy, such as wind energy, poses a challenge because their output is intermittent and variable and must be stored for use when there is demand. If only one renewable energy source is considered, the electric power system is simple where the source can be connected to a storage system. In the grid-connected application, the grid acts as energy storage. However, if multiple renewable energy sources are used, the electric power system can be rather complex and needs detailed analysis.

Wind Energy – SEIG System for Remote Users

An induction generator (IG) requires reactive power whether it is running as a machine or a generator. As mentioned previously, the reactive power needs of the IG in remote user cannot be supplied from the grid and other sources must be used. One possible source might be a three-phase capacitor connected in parallel with the machine, which enables the machine to operate self-excited. Another source may come from a capacitor connected to the dc bus of an inverter. This scheme is able to start the machine as long as there is an initial voltage on the capacitor. However, a more reliable method of starting the machine is to use a battery on the dc bus that can supply voltage until enough voltage is being generated by the machine to power the dc bus [3].

After the machine has started generating voltage, there are several methods for using the power generated by the machine. An ac load can be attached directly to the machine terminals. However, the voltage and frequency of the electrical power on the terminals of the machine depend on the speed. In renewable energy applications such as wind or hydro power generation, the speed of the machine is not constant and consequently poses a problem. A dc load can also be connected on the dc bus of the inverter. However, a controller must be used to regulate the voltage on the dc bus. If the voltage on the dc bus drops too much, the voltage supplied by the machine will collapse and will no longer be able to supply power to the loads [3].

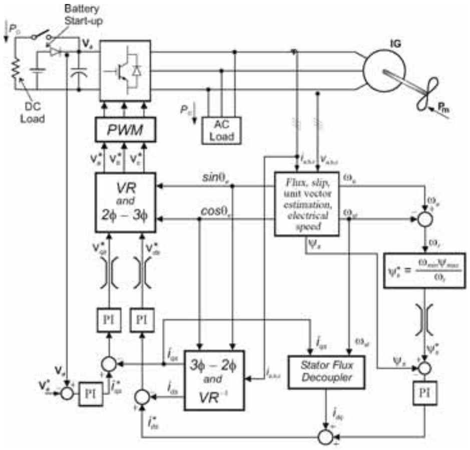

Figure 2. Induction generator with a remote wind energy system

An experimental system with wind energy and induction generator is shown in Figure 2. The system is started by a battery connected to the dc bus, when the voltage on the bus increases above the voltage on the battery, the diode shuts off and the bus is powered from the machine only [3]. In addition to keeping the voltage on the bus constant, the generator also supplies both ac and dc loads. To supply the ac load with power, the controller regulates the voltage on the terminals of the machine. The controller attempts to keep the voltage on the dc bus constant, but also tries to regulate the voltage on the terminals of the machine to supply the ac load with a constant voltage.

The voltage on the ac bus can be controlled indirectly by programming the machine stator flux such as indicated by Equation (2):

$$E \propto \omega_r \Psi \qquad (2)$$

where, E is the no-load voltage, and Ψ is the machine air-gap or stator flux.

This means that the voltage on the terminals is proportional to the rotor speed times the flux. To keep the voltage on the terminals constant, the product of the speed and the flux must remain constant. However, this assumption has limits based on the machine parameters [13]-[15]. The maximum speed is limited by the mechanical rating of the machine. The machine should not be operated above this speed, so this value corresponds to the minimum flux limit. The maximum flux in the machine is limited by saturation effects within the machine. There is a value corresponding to a minimum speed limit that the machine can run while maintaining constant voltage.

The rotor speed is known either from actual measurements or by estimation. Therefore, the following equation can be used to calculate the reference flux for the controller:

$$\psi^* = \frac{\omega_{r,min}}{\omega_r}\psi \qquad (3)$$

All the equations to implement the control system are based on stator flux orientation as explained in [3]. The results from running the simulation are shown in Figure 3 and 4.

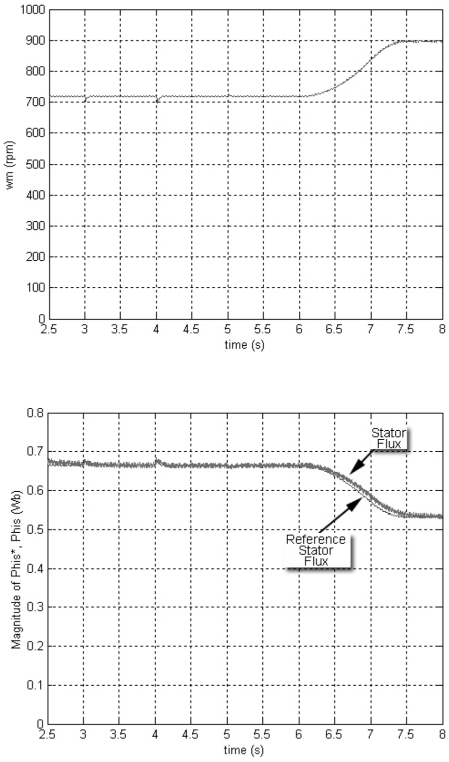

Figure 3. Induction generator operation (a) estimated rotor speed, (b) reference and actual flux

To show the effectiveness of the voltage regulation, consider the voltage waveforms in Figure 4(b). The controller with constant flux varies from 77.0 Vrms to 28.6 Vrms (62.8% drop), while the controller with variable flux varies from 65.2 Vrms to 57.3 Vrms (12.1% drop).

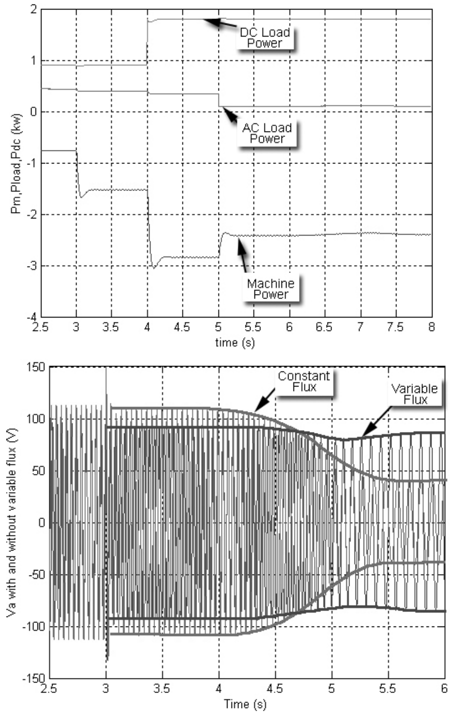

Figure 4. (a) Load powers and machine power, (b) voltage waveforms with and without variable flux

Investment Considerations

In induction generator based renewable energy systems the energy source is typically a low-speed prime mover such as hydropower or wind power. The investments required for such power plants are basically for three areas: (1) a power generation section, consisting of the turbine, gear box, generator and all structural elements to support them, (2) a protective and control operational center capable of withstanding environmental and operational hazards and (3) a utility power interface section, tailoring the power output to the requirements of the electrical grid [1].

One important economic concept that is used to support capital investment analysis is the capacity factor (CF). The capacity factor measures the operational hours, seasonal constraints, and source and demand fluctuations that limit the full utilization of the installed power plant by dividing the actual energy produced during a specified time period by the amount of the energy that would have been produced under full power [1].

$$CF = \frac{ActualEnergy}{EnergyatFullUse} \qquad (4)$$

A wind turbine rated at 100 kW would produce 87600 kWh of electricity per year if operating 100% of time. However, wind velocity fluctuation, maintenance down time and the demand matching will constrain the annual output power to a lower value. For average production, the average input must be computed, and the given average shaft velocity would determine a gearbox that optimizes the power transfer. But the operational generator speed would oscillate about this optimum point, and the electronic system must compensate for such deviation. Therefore, there is a typical cost of energy generated by the system that must be taken into consideration for the amortization of the cost of capital, operation, and maintenance [1].

Since wind power systems do not require fuel for operation, the following equation expresses the cost of energy, neglecting taxes, surcharges, and insurance [16]:

$$C = \left[\frac{r(l+r)^n}{r(l+r^n-1} + m\right]\frac{P}{87.6(CF)} \qquad (5)$$

where, C is generation cost in U.S. cents per kilowatt hour; CF is capacity factor; m is the fraction of the capital costs needed per year for operation and maintenance of the unit; n is the amortization period in years; P is the capital cost in US dollars per kW; and r is the annual interest rate per unit.

Optimization of Control Actions

General approaches of optimization utilize linear, nonlinear, dynamic, and stochastic techniques, while in control, the calculus of variations and optimal control theory are important. Operations research is the specific branch of mathematics concerned with techniques for finding optimal solutions to decision-making problems. However, these mathematical methods are, to a large degree, theoretically oriented and thus very distant from the backgrounds of the decision makers and management personnel in industry. Recently, practical applications of heuristic techniques like hill climbing and fuzzy logic have been able to bridge this gap, thereby creating the possibility of applying practical optimization to industrial applications. One field that has proven to be attractive for optimization is the generation and control of electric power from alternative and renewable energy resources like wind energy [17], [18]. For such generation systems, where the installation costs are very high, while the availability of alternative power is by its nature intermittent, which tends to constrain efficiency. It is therefore of vital importance to optimize the efficiency of electric power transfer, even for the sake of relatively small incremental gains, in order to amortize the installation costs within the shortest possible time. The following characteristics of induction-generator based control motivate the use of heuristic optimization [1]:

- Parameter variation that can be compensated for by design judgment.
- Processes that can be modeled linguistically but not mathematically.
- Dependence on operator skills and attention.

- Process parameters affect one another.
- Effects cannot be attained by separate PID control.
- Data intensive modeling.

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Authors Biographies

M. Godoy Simões (S’89–M’95–SM’98) received the B.S. and M.Sc. degrees in electrical engineering from the University of São Paulo, São Paulo, Brazil, in 1985 and 1990, respectively, the Ph.D. degree in electrical engineering from the University of Tennessee, Knoxville, in 1995, and the Livre-Docencia (D.Sc.) degree in mechanical engineering from the University of São Paulo, in 1998. He joined the faculty of Colorado School of Mines, Golden, in 2000 and has been working to establish research and education activities in the development of intelligent control for high-power electronics applications in renewable and distributed energy systems. Dr. Simões authored the book “Renewable Energy Systems: Design and Analysis with Induction Generators,” by CRC Press, and the book “Integration of Alternative Sources of Energy,” by John Wiley and Sons.

Dr. Simões is a recipient of a NSF - Faculty Early Career Development (CAREER) in 2002, the NSF’s most prestigious award for new faculty members. He served as the Program Chair for the Power Electronics Specialists Conference 2005, as well as the General Chair of the Power Electronics Education Workshop 2005. He is serving as the Chair of the IEEE Power Electronics Chapter of the Denver Section, IEEE Power Electronics Society Intersociety Chairman, and also as the Associate-Editor for IEEE Transactions on Power Electronics.

Sudipta Chakraborty (S’02) was born in Kolkata, India, in 1979. He received the B.E. degree in Electrical Engineering from Bengal Engineering College (now Bengal Engineering and Science University) in 2001. He joined Colorado School of Mines in spring 2002 to pursue PhD degree in Engineering Systems, Electrical Specialty. He is currently working on intelligent integration of renewable sources in the Microgrid so that the power quality and power flow issues can be resolved. His research interests include renewable energy, control systems, power electronics, intelligent control and power systems. Mr. Chakraborty was recipient of several awards and scholarships from the Government of India for his scholastic achievements. In USA he was enlisted in 2002-2003 edition of the National Deans List. A student member of IEEE, he received Myron Zuker Travel Grant from IEEE to attend 38th Annual Meeting of the IEEE Industrial Applications Society held in Saltlake City, UT in 2003. Recently, he was awarded with the IEEE Industrial Electronics Society scholarship to attend and present his paper in IECON 2005 held in Raleigh, North Carolina.

Robert Wood is a member of the Power Components Branch, U. S. Army Research Laboratory, Adelphi, MD, where he is currently the lead for improving DC to AC designs for three phase motor drive inverters through simulations and experimental tests. In addition to inverter design, he also designed and built several DC to DC converters, and programmed several micro-controllers to run various tasks. Preceding his work at ARL, Mr. Wood did research at the Colorado School of Mines on three phase inverters. He simulated and implemented a three phase vector controller designed to generate power from a variable speed shaft. The controller was tested on a three phase inverter running a small induction machine driven by a DC machine. Mr. Wood received his B.S.E.E. and M.S.E.E degrees from the Colorado School of Mines, Golden, Colorado in 2002 and 2004 respectively. Mr. Wood has authored 2 papers and co-authored 2 papers.