Control and Operation of Opti-Slip Induction Generator in Wind farms

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Abstract— **This paper presents an elegant technique for mitigating the output power fluctuations from a grid connected Opti-slip induction generator (OSIG), due to sudden wind gusts leading to input drive torque variations. The proposed technique has also been extended to control the amount of real power into the grid at the desired value. The control of OSIG is achieved using the basic principles of chopper control for varying the rotor resistance. The proposed control scheme has been simulated in PSCAD/EMTDC. The results obtained in simulation are discussed in detail.**

Keywords— ***Wound rotor induction machine, Opti-slip induction generator, input drive torque fluctuations, chopper control.***

I. INTRODUCTION

An ever growing demand for electricity, accompanied with diminishing fossil fuel reserves have attracted the researchers in the past in identifying suitable and viable alternate fuels for power generation technology. Recent technology improvements in micro-turbines, fuel cells, wind, solar and energy storage devices have provided the opportunity for dispersed generation at the distribution level [1]. However, there has been a growing interest in wind energy as it is a potential source for electricity generation with minimal environmental impact. With the advancement of aerodynamic designs, wind turbines can capture hundreds of kilowatts of power. When such wind turbine generator systems (WTGS) are integrated to the grid, they produce substantial amount of power, which can even supplement the base power generated by thermal, nuclear, or hydropower plants [2].

Practically, Induction machines are the popular choice as generators in WTGS in view of their operational, control simplicity together with their rugged construction and low cost. Fixed speed wind turbines are usually equipped with cage rotor induction machines. They draw the required magnetizing current from either the grid or local capacitor banks and they operate close to synchronous speed. However, if there is flexibility in varying the shaft speed, the energy capture due to fluctuating wind velocities can be substantially improved [3]. By using back-to-back PWM converters between the grid and the machine and employing vector control or direct torque control techniques, the active and reactive powers handled by the machine can be controlled independently. This may become uneconomical on account of the ratings of the power electronic devices employed [4].

In practice, variable speed operation of wind turbines are achieved using wound rotor induction machines. Depending on the control technique employed on these wound rotor induction machine, they can be classified as:

- Doubly Fed Induction Generator (DFIG)
- Opti-Slip Induction Generator (OSIG)

With due care and attention in the design of WTGS, use of a slip-ring induction generator is found economically competitive, when compared to a cage rotor induction machine [5]. Since the stator is directly connected to the grid, the stator flux is constant over the entire operating region. Therefore, the torque can be maintained at its rated value even above the synchronous speed. This results in higher power output above the synchronous speed (i.e., at high wind velocities) when compared to a cage rotor induction generator of the same frame size. Thus, the machine utilization is substantially improved. In addition, the power rating of the converters are also considerably reduced (about 0.3 to 0.5 p.u.) when used in the rotor circuit.

DFIG controller and its operation is quite complex requiring large number of power electronic switches on the back to back PWM converter and a power balancing capacitor. However, it provides independent control of real and reactive power flows of the induction machine [6]. On the other hand, the control of OSIG is quite simple requiring less number of power electronic switches in its rotor circuit. Moreover, the stability of the OSIG and the connected power system network can be easily enhanced [7]. Since wind velocity is being subjected to random variations, sudden wind gusts in the wind farm leads to output power fluctuations. This fluctuating power flowing into the grid leads to voltage fluctuations and causes power quality problems. Therefore an attempt has been made in this paper to mitigate output power fluctuations from OSIG under low input drive torque variations using rotor resistance control. Moreover, evacuation of power extracted from the wind is limited in practice by the power carrying capacity of the interconnecting transmission lines. Hence, a simple technique has been proposed to control the power fed into the grid at the desired value. The simulation is carried out using

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PSCAD/EMTDC software. This paper is organized as follows: Section – II gives an overview of various wind turbine topologies. The control scheme employed in this paper is discussed in section-III. The simulation results are discussed in section-IV.

II. Overview of Wind Turbine Topologies

Based on the operating speed ranges, WTGS can be classified into fixed speed and variable speed WTGS [8].

A. *Fixed Speed WTGS*

Fixed-speed wind turbines are usually equipped with a cage rotor induction machine, which is directly connected to the grid with a soft-starter and a capacitor bank for its reactive power requirement as shown in Fig.1. They are designed to achieve maximum efficiency at only one particular wind speed. Though fixed-speed wind turbine has the advantage of being simple, robust and reliable, they have an uncontrollable reactive power consumption, mechanical stress and limited power quality control. Owing to its fixed-speed operation, all fluctuations in the wind speed are further transmitted as fluctuations in the mechanical torque and then as fluctuations in the electrical power on the grid.

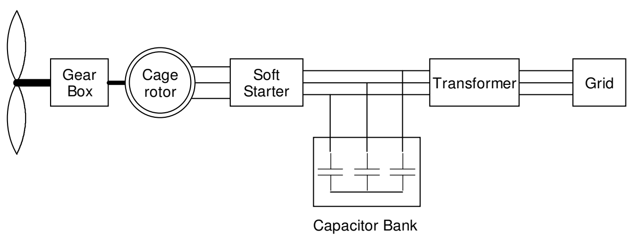

Fig.1 Fixed-Speed WTGS with Cage Rotor Induction Machine.

B. *Variable Speed WTGS*

Variable speed WTGS are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. In contrast to fixed-speed WTGS, a variable-speed WTGS keeps the generator torque fairly constant and the variations in wind are absorbed by changes in the generator speed. The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics devices, high equipment costs with use of more components.

Based on the use of power electronic controls employed in WTGS, variable speed WTGS can be classified as below and are shown in Fig.2 to 4.

- Variable speed WTGS with full converter
- Doubly fed induction generator (DFIG)
- Opti-slip induction generator (OSIG)

Variable speed WTGS with full converter as shown in Fig. 2 is highly uneconomical on account of the cost of power electronic components involved.

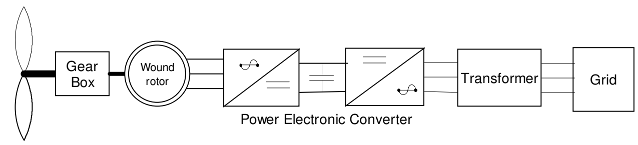

Fig.2 Variable-speed wind turbine with full converter

On the other hand, the implementation of controllers for DFIG as shown in Fig. 3 is much more complicated than that of an OSIG.

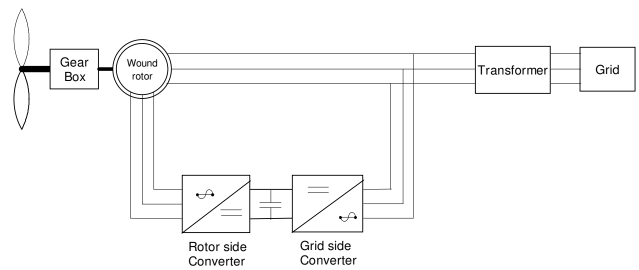

Fig.3 Doubly fed induction machine

Under conditions, where independent control of real and reactive powers of WTGS is not of great importance, an OSIG is preferred in terms of reduced control complexity, installation cost, operational cost and number of power electronic switches.

OSIG are wound rotor induction machines with an external rotor resistance connected to the rotor windings as shown below in Fig. 4. This feature allows the generator to have a variable slip (narrow range) and to choose the optimum slip. The slip of the generator is varied by changing the rotor circuit resistance with a power electronic device mounted on the rotor shaft. The stator of the generator is directly connected to the grid [8].

Some of the advantages of the OSIG are:

- A simple circuit topology.
- An improved operating speed range compared with SCIG.
- OSIG can reduce the mechanical loads and power fluctuations caused by gusts. However, it still requires a reactive power compensation system.

However, OSIG suffers from some of the disadvantages as:

- The speed range is typically limited to 0-10%
- Poor control of active and reactive power.
- Slip power is dissipated in the variable resistance as losses.

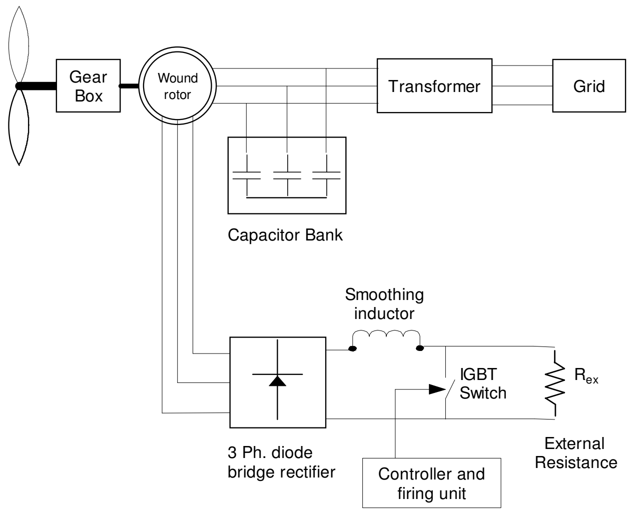

Fig. 4 Opti-slip induction generator

III. Proposed Control Scheme

A rotor resistance control scheme using IGBT switch based on stator power measurement for OSIG have been proposed in this section so as to mitigate any power quality deviations under low input drive torque fluctuations and to keep the power fed into the grid at the desired value, typically up to 25% of the machine ratings.

The control circuit of an OSIG consists of a three phase diode rectifier, an IGBT switch and an external resistance connected at the slip rings of the rotor as shown in Fig. 4. The rotor voltages at slip frequency are converted to dc using three-phase diode bridge rectifier. The duty cycle of the IGBT switch controls the average external resistance connected to the rotor circuit of the induction machine.

Let us define the duty ratio 'α' as

$$\alpha = \frac{T_{ON}}{T} \quad (1)$$

where T_{ON} - On period of IGBT switch

T - Switching Time period of IGBT switch

The average value of resistance Ravg is given by eqn. (2),

$$R_{avg} = R_{ex}(1\text{-}\ \alpha) \quad (2)$$

where R_{ex} – External resistance connected to rotor circuit.

By varying the duty ratio 'α', the external resistance available in the rotor circuit can be varied from zero to its maximum value (R_{ex}). The average power absorbed by the rotor (P_r), is given by eqn. (3),

$$P_r = I_r^2 R_{ex}(1-\alpha) \quad (3)$$

where I_r - per phase rotor current

Per-phase mechanical power input (P_m) to the machine is given by eqn. (4),

$$P_m = (1-(-s))P_g \quad (4)$$

or, $$P_m = (1+s)P_g \quad (5)$$

Also, $$P_m = T_e * \omega_m \quad (6)$$

where s - slip of the induction machine

P_g - Air gap power developed in the induction machine

T_e - Electromagnetic torque developed in the machine

ω_m - Mechanical speed of the rotor

Therefore, any variations in input drive torque will result as output power fluctuations in the grid. In order to maintain the output power constant, the generator electromagnetic torque has to be maintained constant, which is achieved by varying the slip (or rotor resistance) with the help of IGBT switch.

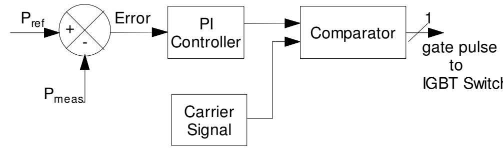

Fig. 5 Rotor resistance control scheme of OSIG

Fig. 5 shows the block diagram of rotor resistance control scheme. Any wind speed variations will result in input drive torque fluctuations and may result in output power fluctuations from OSIG. This power fluctuation produces an error signal at the input of the Proportional and Integral (PI) controller. This in turn generates the duty cycle and the corresponding gate pulses for the IGBT switch connected in the rotor circuit of the induction machine. Thus the average rotor resistance alters such that the electromagnetic torque developed in the induction machine remains constant, in spite of any input mechanical torque variations.

IV. Simulation Study

The simulation study of the proposed technique on OSIG is carried out in PSCAD/EMTDC for the following cases:

Case I: Effect of input drive torque fluctuations

(1) without controller

(2) with rotor resistance control scheme

CaseII: Power flow control of OSIG using rotor resistance control scheme.

The system considered in this paper for investigation of proposed control scheme is given in the appendix. The various case studies are dealt as below. The simulation results are presented in per unit.

A. Case-I: Effect of input drive torque fluctuations

1) without controller

Fig. 6 shows the PSCAD simulation of the system considered for studying the effect of variation in input drive torque fluctuations. Fig. 7 shows the input torque variations and the corresponding output power fluctuations from OSIG.

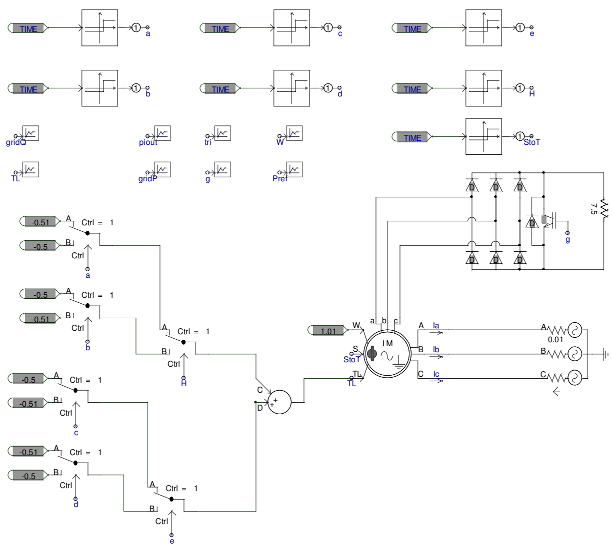

Fig. 6 Simulation model of input drive torque fluctuations

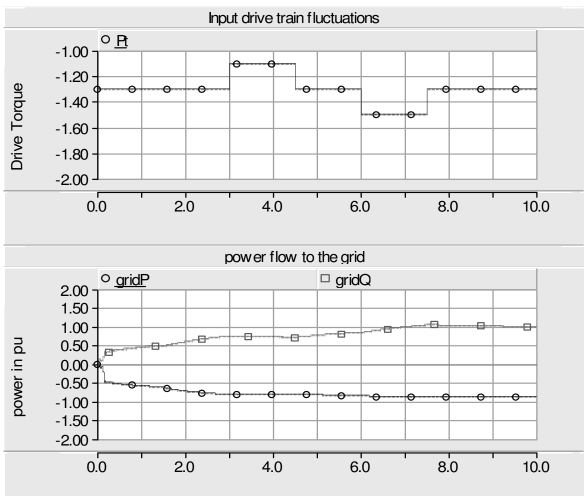

Fig. 7 Simulation results depicting the effect of input drive torque fluctuations on the power output of OSIG

2) *with rotor resistance control scheme*

The rotor resistance control method implemented in PSCAD is shown in Fig. 8. It can be observed from the simulation that the power fluctuations due to input drive torque fluctuations is completely mitigated using rotor resistance control scheme.

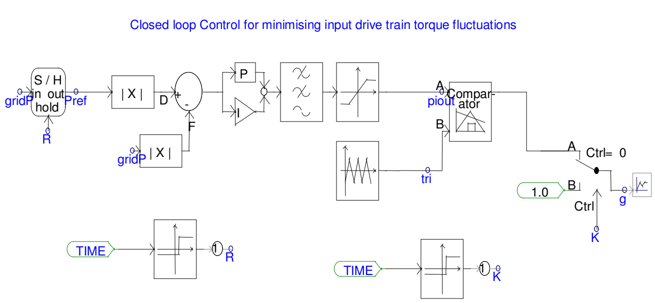

Fig. 8 PSCAD simulation of closed loop direct rotor resistance control scheme of OSIG

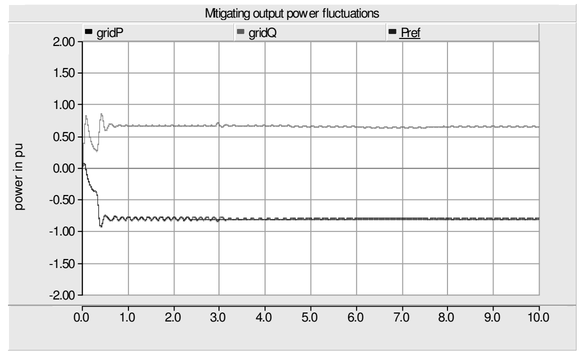

Fig. 9 Simulation results with rotor resistance control scheme for mitigating output power fluctuations with OSIG

B. *Case-II: Power Flow Control of OSIG with direct rotor resistance control scheme*

OSIG can be used effectively to control output power typically over a narrow range of upto 25% of the machine rating. The model used for simulation study in PSCAD is shown in Fig. 10. The power flow control is achieved with the help of rotor resistance control as shown in Fig. 11. It can be found from the simulation result that as the reference power output is changed from 0.75p.u. to 0.60p.u, 0.60p.u. to 0.75p.u. at 5 and 8 seconds respectively, the output power changes immediately as shown in Fig. 12.

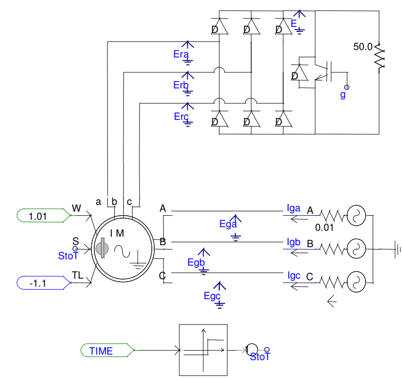

Fig. 10 Simulation model of power flow control of an OSIG

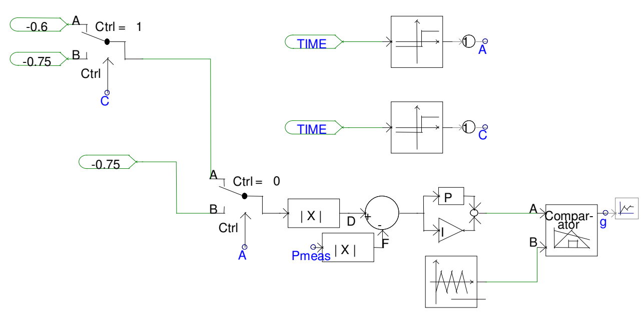

Fig. 11 PSCAD simulation of closed loop direct rotor control scheme for power flow control of an OSIG

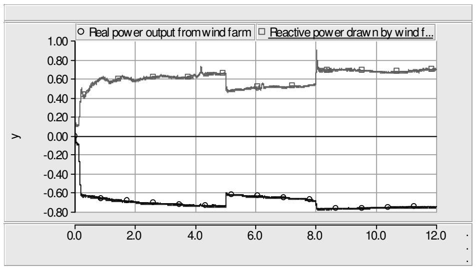

Fig. 12 Simulation result for closed loop power flow control

V. Conclusion

Rotor resistance control scheme was proposed for control and operation of an opti-slip induction generator in wind farms. The performance of the proposed control scheme was investigated for mitigation of output power fluctuations due to input torque variations and also the effectiveness to maintain the desired real power flow to the grid is also examined. The investigations are carried out using simulation in PSCAD/EMTDC software in the laboratory. As the proposed control schemes are quite simple, their use in wind farms is highly appreciable.

Appendix

Parameters of Wound Rotor Induction Machine

Rated power	=	3.75 kW
Rated voltage (L-L)	=	0.415 kV
Base angular frequency	=	314 rad. /sec
Stator/rotor turns ratio	=	2
Stator resistance	=	7.50 Ω
Rotor resistance	=	0.75 Ω
Magnetizing inductance	=	449.07 Ω
Stator leakage inductance	=	12.82 Ω
Rotor leakage inductance	=	12.82 Ω

3-phase voltage source model (Grid)

Source impedance type	=	R
Base MVA (3-phase)	=	0.00373MVA
Base voltage (L-L, RMS)	=	0.415Kv
Base frequency	=	50Hz

Control Scheme

Proportional Gain	=	6
Integral Gain Constant	=	0.91 sec

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