Analysis and Performance of 3-Phase Grid-Connected Induction Generator via Transistorized AC Voltage Controller

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ABSTRACT

This paper presents a complete analysis of induction generator connected to the grid through a transistorized AC voltage controller. Two different control strategies are used to control the voltage of induction generator. The performance characteristics regarding harmonic contents, active and reactive powers, power factor and efficiency have been computed. These characteristics have been determined for a wide range of operating conditions through a simulation computer program. The validity of the model and results has been confirmed experimentally.

Keywords: induction generator, AC voltage controller, grid-connected.

1. INTRODUCTION

Induction generators have two modes of operation. They are either autonomous or grid-connected units. The power factor of the grid-connected induction generator is fixed by its slip and its equivalent circuit parameters and not affected by the load [1]. The quadrature component of the output current is nearly constant for any fixed terminal voltage and frequency and leads the voltage. It is necessary therefore to operate such generators in parallel with synchronous machines. These synchronous machines do not only supply the quadrature lagging current demanded by the load but also supply sufficient quadrature lagging current to neutralize the quadrature leading component of the current delivered by the induction generator. Thus, the synchronous machines in parallel with an induction generator determine its voltage and frequency, while its output is fixed by its slip [1]. Induction generator when driven by wind turbine is liable to run near its synchronous speed when the wind speed is low. This results in operation at bad power factor and low efficiency. To overcome this drawback of the generator at such loads, it is recommended to lower its terminal voltage. Thus an AC voltage controller used as an interface between the network and the generator is useful in this concern [2-4]. In a previous work by the authors, an AC voltage controller utilizes a set of two anti-parallel thyristors in each phase has been used to link the induction generator to the grid [5-6]. Phase angle control was used to control the voltage of induction generator.

In the present paper, another simple AC voltage controller is used to control the active and reactive power of an induction generator connected to the grid. The AC voltage controller utilizes a set of IGBT devices in each phase and different control strategies are applied. The performance of grid-connected induction generator is studied through modeling it by a novel equivalent circuit in a pseudo-stationary abc-dq reference frame. Based on the circuit model a state space mathematical model is developed. The model is capable of dealing with the nonlinearities introduced by the used electronic solid-state switches. The performance characteristics have been computed for a wide range of operating conditions through a simulation computer program. In addition to the simulation process an extensive laboratory experiments have been carried out to insure the validity of the proposed system and its model.

2. PROPOSED CONTROL SCHEME

The proposed scheme is shown in Figure 1. Each stator phase has a control circuit that contains series and shunt IGBT (Isolated Gate Bipolar Transistor) in bridge of diodes to unify the direction of current. This control circuit links the induction generator to the grid. The terminal voltage as well as the active and reactive powers of the generator can be controlled by variation the on and off periods of the series IGBT. The shunt IGBT allows the clamped current in the stator-phase to continue flowing during the off state of the series IGBT. Two control strategies are proposed [7]:

A) Firing angle control: the control of the generator terminal voltage is done by variation of the firing angle (α), while the extinction angle (β) is fixed at 180 degrees as shown in Fig. 2(a).
B) Extinction angle control: the control is done by variation of the extinction angle (β) while the firing angle (α) is fixed at zero as shown in Fig. 2(b).
3. RESULTS AND DISCUSSION

A computer program has been developed to simulate the proposed system. Numerical integration using the forth order Runge-Kutta algorithm has been applied to compute the currents step by step in the time domain. Standard numerical techniques have been applied to calculate the average developed torque, supply and stator-phase (rms) currents, harmonic factor, power factor, displacement angle, active and reactive powers, and the generator efficiency.

A three-phase squirrel cage induction generator having the specifications and parameters given in Table 1, has been used for computations and experimental work. The performance characteristics have been computed at different speeds and different conduction angles. The results are given below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{rated}}$</td>
<td>380 V</td>
</tr>
<tr>
<td>$I_{\text{rated}}$</td>
<td>6.9 A</td>
</tr>
<tr>
<td>$f$</td>
<td>60 Hz</td>
</tr>
<tr>
<td>$R_g$</td>
<td>0.065024 pu</td>
</tr>
<tr>
<td>$X_d$</td>
<td>0.06527 pu</td>
</tr>
<tr>
<td>$X_{\text{base}}$</td>
<td>1.07196 pu</td>
</tr>
<tr>
<td>$P_{\text{base}}$</td>
<td>3000 W</td>
</tr>
</tbody>
</table>

### i) Fundamental Current Characteristics

Figure 3 shows the variation of the fundamental component of generator current versus the conduction angle. The current decreases by decreasing the conduction angle ($\gamma$) and increases by increasing the rotor speed for both control strategies. The fundamental component of supply current generally behaves in a manner similar to that of fundamental component of generator current as shown in Fig. 4 but, in case of firing angle control strategy, a fluctuation will happen when ($\alpha > 60^\circ$). The measured currents follow the same behavior of the computed results. When the conduction angle ($\gamma$) decreases to less than $90^\circ$ the currents start dropping rapidly then the generator enters to the infeasible operation region. In this region the generator is unstable. Accordingly, the experimental readings in this region can not be measured.

### ii) Harmonic Factor Characteristics

The harmonic factor of generator current as shown in Fig. 5 increases as the conduction angle decreases, also it decreases as the rotor speed increases for both control strategies. The harmonic factor of supply current as shown in Fig. 6 behaves in a manner similar to generator harmonic factor if the generator still operates in the feasible operation region for both control strategies. But when the generator approaches to the infeasible operation region, the supply harmonic factor will fluctuate then increases naturally in firing angle control strategy, while in extinction angle control strategy the supply harmonic factor increases rapidly to high value.
iii) Displacement Angle Characteristics
For both control strategies, the phase shift between the fundamental of supply current and the supply voltage (displacement angle) decreases as the conduction angle decreases over a certain range of conduction angle then increases to value more than 100°, also the displacement angle decreases by increasing the rotor speed as shown in Fig.7.

iv) Active Power Characteristics
As shown in Fig. 8 the output power of induction generator increases by increasing the rotor speed but decreases by decreasing the conduction angle for both control strategies. When the generator operates at small conduction angle, the output power will be very small and may go to negative value at low rotor speeds, this is because the generated power is not enough to cover the internal losses of the machine. Accordingly, the generator will absorb active power from the grid, which leads to negative power factor. Thus the operation in this region is considered infeasible and the generator will be unstable. The experimental readings in this region can not be measured.

v) Reactive Power Characteristics
The induction generator consumes reactive power as shown in Fig. 9. Generally the consumed reactive power decreases by decreasing the conduction angle, also it decreases by decreasing the rotor speed for both control strategies. But in case of firing angle control when (α > 30°) a fluctuation will happen then the consumed reactive power will decrease by increasing the rotor speed, while in extinction angle control when (β<150°) the consumed reactive power will increase by decreasing the conduction angle. The measured readings follow the computed results in the feasible operation region.

vi) Power Factor Characteristics
As shown in Fig. 10 the power factor starts at low values then increases by decreasing the conduction angle up to the middle of feasible operation region then decreases rapidly to negative values in the infeasible operation region. Also it increases by increasing the rotor speed. This behavior is noticed for both control strategies.

vii) Efficiency Characteristics
The efficiency behaves in a manner similar to that of active power (Fig.8) as shown in Fig. 11. If the generator operates in the feasible operation region, the efficiency is high then goes to negative values when the direction of active power reversed for both control strategies. For the machine under investigation there are two operation regions. The first one is the feasible operation region where the generator supplies power to the grid. The second is the infeasible operation region where the direction of active power reversed, this region starts at conduction angle (γ) less than 120° for rotor speed of 1.01 pu for both control strategies. The infeasible operation region decreases by increasing the rotor speed. Also the current exceeds the rated value at rotor speed greater than 1.03 pu. So the maximum rotor speed for the machine is 1.03 pu.

4. CONCLUSIONS
The paper has presented a complete analysis of induction generators connected to the grid through a solid state AC voltage controller. The used mathematical model is capable of representing the steady state conditions of 3 phase grid-connected induction generator when static voltage controller is connected to its stator terminals. This controller uses the isolated gate bipolar transistors (IGBT) as switches. The controller enables the control of active and reactive powers delivered by the generator to the grid. Firing angle control strategy and extinction angle control strategy have been used.

From the computed and measured performance characteristics, the followings are concluded:

i- The feasible operation region is the region where power factor and efficiency is high.
ii- By using the proposed scheme, it is possible to get constant output power for a certain range of rotor speed by varying the conduction angle.
iii- Also, it is possible to avoid the inrush current at the instant of interaction between the induction generator and the grid by applying the voltage gradually.
iv- The existence of semiconductor switching is associated with existence of harmonic contents.
v- The third harmonic and its multiples in supply current may be eliminated easily when a star-delta transformer is used for connection with grid.
vi- Experimental measured results verify the validity of the proposed scheme and its model.

5. ACKNOWLEDGEMENT
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6. REFERENCES


Fig. 3: Variation of fundamental component of Ig versus conduction angle

Fig. 4: Variation of fundamental component of Is versus conduction angle

Fig. 5: Variation of harmonic factor of Ig versus conduction angle
Fig. 6: Variation of harmonic factor of $I_s$ versus conduction angle

Fig. 7: Variation of displacement angle versus conduction angle

Fig. 8: Variation of active power versus conduction angle
Fig. 9: Variation of reactive power versus conduction angle

Fig. 10: Variation of power factor versus conduction angle

Fig. 11: Variation of efficiency versus conduction angle