CHAPTER 6

DESIGN AND DEVELOPMENT OF DOUBLE WINDING
INDUCTION GENERATOR

6.1 INTRODUCTION

Conventional energy resources are not sufficient to meet the increasing electrical power demand. The usages of non conventional energy become necessary to bridge power crisis. Wind energy provides opportunity to share the power demand. Induction generators are dominating as major power supplying units.

Non-conventional resources becoming conventional resources without which the increasing electrical power demand cannot be met with. Induction generators are often used in wind turbines due to their ability to produce real power at varying speeds. Induction generators are excited externally to produce a rotating magnetic field.

While operating as an induction generator, the reactive power is supplied externally either from electrical grid or from externally connected capacitor bank. Induction generators are rugged in construction, requiring no brushes and commutators.
6.1.1 Need for Induction Generator

In order to meet required power demand and to feed rural areas, induction generators may be employed. Compared to conventional synchronous generators, induction generators have the following advantages:

i) No sustained short circuit current problem
ii) Elimination of synchronizing problem
iii) Elimination of hunting problem
iv) Extraction of more power from the machine compared to motor operation.

6.1.2 Advantages and Disadvantages of Induction Generator

Induction generator can also be operated in parallel with synchronous generator to supplement the increased power demand. The importance of any generator depends on factors such as primary source, type of load, and speed of the turbine. In comparison with other generators, induction generators are simple in construction, capability to run independently, less expensive compared to conventional synchronous generators, stand-alone operation and no fixed frequency, less maintenance and only electro magnets are used. Though there are various advantages, still induction generators suffer from poor power factor, voltage and frequency regulation. Also, reactive energy is to be supplied from the grid or capacitor bank.

6.1.3 Classification of Induction Generators

Induction generators can be classified based on rotor construction, excitation, and type of prime movers used. Based on rotor construction, induction generators are classified as squirrel cage induction generator in
which rotor core is filled with aluminum or copper bars in the rotor slots which are short circuited using end rings and wound rotor induction generator in which the rotor is wound for similar number of poles as in the stator.

Based on excitation, induction generators are classified as Grid connected induction generator and Self-excited induction generator. When an induction motor is driven above the synchronous speed, it receives the reactive power from the grid and supplied real power to the load. The simple arrangement of grid connected induction generator is shown in Figure 6.1. The operation of grid connected system is comparatively simple as the voltage and frequency are controlled by the grid.

![Grid connected induction generator](image)

**Figure 6.1 Grid connected induction generator**

Figure 6.2 shows self-excited induction generator in which reactive power is supplied from a capacitor bank, connected across stator terminals.
6.2 DESIGN PROCEDURE

6.2.1 Objective of proposed model

Elder et al (1984) presented the use of self-excited induction machines as low-cost stand-alone generators. They have dealt with problem faced in guaranteeing excitation and residual magnetism. Suitable VAR sources have been suggested to control the excitation in order to maintain better regulation.

Murthy et al (1988) presented suitability of using a normal three-phase induction motor as a capacitor self-excited induction generator. It was found that, for low power motors, the maximum power that can be extracted as generators is 148% to 160% of the motor rating for resistive loads and 118% to 128% of motor rating for 0.8 lagging power factor loads.

Compared to other generators, induction generators are very simple in construction both in terms of mechanical and electrical. Bansal (2005) compared the process of self-excitation and voltage buildup, modeling, steady-state, and transient analysis, reactive power control methods and parallel operation of Self Excited Induction Generator (SEIG). Due to

![Figure 6.2 Self-excited induction generator](image-url)
simplicity, induction generators can be operated in stand–alone mode to supply power to remote area so as to meet excessive load demand.

The design requirement of the self-excited capacitor in a dual-stator winding induction generator (DSWIG) is different from that of the conventional induction generator. Wang et al (2008) considered efficiency optimization as design aim for a self-excited capacitor for dual stator winding induction generator.

In Steinmetz scheme, the induction motor may be regarded as a direct evolution from the DC shunt motor. Implementation of balanced version of induction generator in Steinmetz scheme is aimed to prevent complete de-excitation in the core, improve load ability, better voltage stability with maintained core saturation, constant speed operation and improved power factor in grid connected operation.

A conventional induction machine consists of a three phase winding that carries both excitation current and load current. Proposed scheme involves provision of an extra three-phase winding in the same stator. Provision of an extra winding offers the following features as

i) The exciter and load winding are magnetically coupled, with transformation of almost unity. Under balanced condition, neglecting the effect of space and phase shift between the windings, the voltage that is induced across both the windings would be almost same.

ii) When both the windings are excited magnetically, core saturation can be achieved effectively than in a single wound stator.
iii) Under the saturated conditions, the drop due to the synchronous reactance remains within a particular range

iv) The capacitance requirement for the excitation in a doubly wound machine is comparatively less than that of the single wound machine

v) Since the excitation is distributed across the windings, the regulation will be better even for reactive loads.

6.2.2 Scope of the suggested model

By providing an additional three phase winding in the same stator, voltage stability of induction machine as a self excited generator is analyzed. Design considerations such as better cooling to improve machine rating, effect of phase and space shift between the two windings have been neglected. Since the research deals with modification of existing machine and not complete construction, the magnetizing characteristics and the dimension of the existing machine had to be complied with.

The design of the induction generator involves the study of suitability of conventional induction motor. The principle limiting factor in such application is the thermal limit of stator windings. Therefore it is evident that the induction motors can be used in generation mode only for low power operations.

In stand-alone system, excitation is supplied to stator of induction machine, therefore under heavy reactive load, machine gets de-excited. Due to small air-gap, machine offers high reactance, which leads to poor voltage regulation.
As a separately excited grid connected system, power factor does not depend on load but slip. For every load, there is unique power factor, which is out of control. Since excitation and working current, flow through the same winding the power factor is poor.

6.2.3 Design Specifications

Capacity of the machine: 2.2 kW, 3-phase, 415 V, 4.5 A, 50 Hz, 4-pole squirrel cage induction motor.

The main dimensions of the machine

- Diameter of the bore = 0.17 m
- Length of the core = 0.10 m
- Turns per phase \( T_s \) = 396
- Number of stator slots = 36
- Slot depth 17 mm and slot width 5mm
- Flux density in core \( B_{av} \) = 1.0 Wb/m²
- Current density in the winding = 6.0 A/mm²
- Flux in the air gap \( \Phi \) = 2 x Core depth x Length of core x \( B_{av} \)
  = 2 x 1.7 x 10^{-2} x 10 x 10^{-2} x 1
  = 34 x 10^{-4} Wb

Design of exciter winding

\[ E_s = 4.44 \times f \times \Phi \times T_s \times k_w \]

400

\[ = 4.44 \times 50 \times 34 \times 10^{-4} \times T_s \times 0.95 \]
$T_s = 589$ There are 12 coils

Turns per coil = 49

The excitation winding is connected in delta with 22 SWG

Current in the exciter winding $= 6 \times \pi \times (0.711)^2 / 4 = 2 \text{ A}$

**Design of load winding**

$(400/\sqrt{3}) = 4.44 \times 50 \times 34 \times 10^{-4} \times T_s \times 0.95$

Turns per phase $T_s = 340$

The number of turn per coil $= 28$ (20 SWG)

Current in the load winding $= 6 \times \pi \times (0.914)^2 / 4$

$= 4\text{A}$

These two windings are placed in the stator core as two double layered windings, with load winding at the bottom and the excitation winding occupying the top position.

### 6.2.4 Determination of Critical Capacitance

A simple algorithm has been developed to predict the minimum value of capacitance necessary for self-excitation and to maintain the generator terminal voltage at a preset value under specific load and speed conditions (Harrington et.al 1998). In order to determine equivalent circuit parameters, no load and blocked rotor tests are carried out. Test results are shown in Table 6.1
Table 6.1 No load and blocked rotor test (IG)

<table>
<thead>
<tr>
<th>Test</th>
<th>Voltage(V)</th>
<th>Current(A)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load</td>
<td>415</td>
<td>1.45</td>
<td>184</td>
</tr>
<tr>
<td>Blocked rotor</td>
<td>180</td>
<td>4.0</td>
<td>640</td>
</tr>
</tbody>
</table>

From no load

\[ X_0 = \frac{V_{ph}}{I_{ph}} = 159.27 \Omega \]

From blocked rotor test

\[ Z_{ph} = \frac{V_{ph}}{I_{ph}} = 25.98 \Omega \]

\[ R_s + R_r = \frac{w_{sc}}{3 I_{ph}^2} = 13.33 \Omega \]

\[ X_s + X_r = \sqrt{(Z_{ph}^2 - R_{ph}^2)} \]

\[ X_s = X_r = 11.15 \Omega \]

\[ X_M = X_0 - X_s = 148.12 \Omega \]

Power rating

\[ = \sqrt{3} \times 400 \times 4 = 2771.2 \text{ VA} \]

\[ Z_b \text{ characteristics impedance} = \frac{V_{ph}^2}{\text{VA}} = 57.73 \Omega \]

Figure 6.3 shows equivalent circuit of induction machine considering load winding. Per unit values, considering power rating are as follows:

\[ R_s = 0.084 \text{ p.u} \]

\[ R_r = 0.147 \text{ p.u} \]

\[ X_M = 2.56 \text{ p.u} \]

\[ X_s = X_r = 0.193 \text{ p.u} \]
From the equivalent circuit, the minimum value of exciting capacitor can be determined.

\[ C_{\text{min}} = \frac{1}{2\pi f Z_b X_c} = 23.12\mu F \]

A capacitor bank has been designed with different tapings based on this value of capacitance. \( X_c \) is capacitive reactance.

![Figure 6.3 Equivalent circuit of Load winding (IG)](image)

6.3 TESTING

In order to determine the performance of double winding induction generator, series of testing have been carried out. Considering each winding individually, magnetization characteristics were obtained. Table 6.2 shows the change of output voltage with exciting current, corresponding magnetization characteristic is shown in Figure 6.4.
Table 6.2 Magnetization characteristics of excitation winding

<table>
<thead>
<tr>
<th>Exciting current (A)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.52</td>
<td>120</td>
</tr>
<tr>
<td>0.84</td>
<td>200</td>
</tr>
<tr>
<td>0.94</td>
<td>240</td>
</tr>
<tr>
<td>1.48</td>
<td>360</td>
</tr>
<tr>
<td>1.65</td>
<td>400</td>
</tr>
<tr>
<td>1.84</td>
<td>440</td>
</tr>
<tr>
<td>1.95</td>
<td>460</td>
</tr>
</tbody>
</table>

Figure 6.4 Magnetization characteristics of load winding (IG)
Table 6.3 Single winding induction generator with resistive load

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Voltage (V)</th>
<th>Load Current (A)</th>
<th>Capacitance (µF)</th>
<th>Exciting current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1407</td>
<td>415</td>
<td>0</td>
<td>24</td>
<td>0.62</td>
</tr>
<tr>
<td>1384</td>
<td>415</td>
<td>0.6</td>
<td>26</td>
<td>0.63</td>
</tr>
<tr>
<td>1320</td>
<td>415</td>
<td>1.0</td>
<td>30</td>
<td>0.64</td>
</tr>
<tr>
<td>1275</td>
<td>415</td>
<td>1.6</td>
<td>36</td>
<td>0.64</td>
</tr>
<tr>
<td>1225</td>
<td>415</td>
<td>2.0</td>
<td>42</td>
<td>0.64</td>
</tr>
<tr>
<td>1200</td>
<td>415</td>
<td>2.5</td>
<td>50</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Figure 6.5 Capacitance characteristics (SWIG)
Table 6.4 Double Winding Induction Generator with resistive load

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Voltage (V)</th>
<th>Load Current (A)</th>
<th>Capacitance (µF)</th>
<th>Exciting current(A)</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1360</td>
<td>415</td>
<td>1.1</td>
<td>10</td>
<td>0.58</td>
<td>0.91</td>
</tr>
<tr>
<td>1370</td>
<td>415</td>
<td>1.7</td>
<td>16</td>
<td>0.54</td>
<td>0.97</td>
</tr>
<tr>
<td>1378</td>
<td>415</td>
<td>2.2</td>
<td>16</td>
<td>0.52</td>
<td>0.98</td>
</tr>
<tr>
<td>1370</td>
<td>415</td>
<td>2.7</td>
<td>22</td>
<td>0.52</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Figure 6.6 Capacitance characteristics (DWIG)
6.3.1 Performance comparison and inferences

Major observations based on the test results

Load ability:

Considering single winding induction generator, with reference to Table 6.2 for a load current of 2A,

Voltage per phase = 230 V
Exciting capacitance = 42µF
Capacitive reactance = 0.013 Ω
Exciting current = 3.0A
Load current = 2A
Total load current = 3.61A

Considering double winding induction generator, with reference to Table 6.3 for a load current of 2.2A,

Voltage per phase = 230 V
Exciting capacitance = 16µF
Capacitive reactance = 0.005024 Ω
Exciting current = 1.16A
Load current = 2.2A
Total load current = 2.48A
For a given load, the total current in the double winding induction generator is comparatively less than the single winding induction generator. Therefore rating versus volume of material is reduced in double winding induction generator. Value of exciting capacitor for single winding induction generator is 42µF, whereas for double winding induction generator it is 16µF. Major objectives are verified practically.

Controllability of voltage is much smoother in a double winding induction generator than the conventional induction generator. Constant frequency and voltage operation is possible by reducing the capacitance so that the machine operates at a lesser slip. Since the excitation component is supplied in the separate set of winding, there is improvement in the power factor.

6.4 SUMMARY

The provision of an additional winding in the stator has improved the load ability of the induction machine as a generator. The experimental results also illustrate the capability of this machine to operate as constant frequency, constant voltage source. Though this property depends on characteristics of the prime mover. The separation of excitation in the grid connected operation yields a marginally better power factor. The controllability of power factor can be obtained using power electronic converters.

By proving an extra winding, excitation component is isolated from the grid which overcomes the problem of drawing reactive power from the grid. The voltage stability is achieved without compromising the power quality and without subjecting any complications on the existing system.