

INVESTIGATION OF GRID CONNECTED SIX-PHASE INDUCTION GENERATOR FOR SMALL HYDRO POWER PLANTS

Ph. D. THESIS

by

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A THESIS

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ABSTRACT

The increasing importance of fuel saving has been responsible for the revival of interest in so-called alternative source of energy. Thus the drive towards decentralization of power generation and increasing use of non-conventional energy sources such as wind energy, bio-gas, solar and hydro potential, etc. has become essential to adopt a low cost generating system, which is capable of operating in remote areas, and in conjunction with the variety of prime movers. With renewed interest in wind turbines and micro-hydro-generators as an alternate energy source, the induction generators are being considered as an alternative choice to the well-developed synchronous generators because of their lower unit cost, inherent ruggedness, operational and maintenance simplicity. The induction generator's ability to generate power at varying speed facilitates its application in various modes such as a self-excited stand-alone (isolated) mode; in parallel with synchronous generator to supplement the local load, and in grid-connected mode.

Electric power systems have largely developed as three-phase systems both for historical reasons (because the public electric supply is either three-phase or single-phase) utility and for reasons of economy (because standard components may hopefully be used). With the growth of increasingly sophisticated design methods and increased importance of economic, environmental and several other factors, the multi-phase systems are being considered as one of the potential alternatives to conventional three-phase system. In a multi-phase induction machine (comprising of more than the conventional three phases), it is possible to have a significant improvement in system performance with appropriate winding displacements. Double three-phase induction machine is the most representative one of multi-phase machine. It has two sets of three-phase stator windings, which have 30° electrical angle in the space and the isolation in midpoint. This structure can eliminate the torque ripple of six harmonic existing in electromagnetic torque; it eliminates the $6n \pm 1$ ($n = 1, 3, 5, \dots$) harmonic existing in the air-gap flux linkage simultaneity. The technology of multi-phase induction machine, once developed to the stage of practical application, has many advantages to offer over conventional systems.

In recent times, because of inherent advantageous features of multi-phase machines, interest in the use of multi-phase generators has emerged, in conjunction with renewable

electrical energy generating sources. It needs to be emphasized though there is no evidence at present of any industrial uptake of such solutions, multi-phase ac generator (synchronous as well as induction) may become a viable solution for the direct driven applications in wind and hydro powered plants. In last five years, some theoretical and practical works on six-phase self-excited induction generator (SPSEIG) for stand-alone renewable energy generation have been reported. Theoretical works are focused on mathematical modeling of six-phase self-excited induction generator to analyze the transient/dynamic and steady-state behavior of the machine, whereas in practical works, detailed performance analysis of six-phase self-excited induction generator has been presented. However, to the best of the author's knowledge, no theoretical or experimental work on the grid-connected six-phase induction generator (GCSPIG) has been reported so far. In view of this, there is strong motivation to undertake a detailed and systematic investigation on grid-connected six-phase induction generator.

The first part of the work, therefore, presents the mathematical modeling of a saturated grid-connected six-phase induction generator for transient and dynamic analysis of the grid-connected six-phase induction generator. The machine under consideration has six stator phases divided into two wye-connected three-phase sets, labeled *abc* and *xyz*, whose magnetic axis are displaced by an arbitrary angle. The windings of each three-phase set are uniformly distributed and have axes that are displaced by 120° .

Performance equations for this machine are given, which utilize the saturated magnetizing inductance $L_m = (\lambda_m / i_m)$ and its derivative (dL_m / di_m) rather than dynamic inductance $(d\lambda_m / di_m)$. Modeling of the GCSPIG is based on two-axis (*d-q*) model of the machine. From dynamic model of GCSPIG, steady-state analytical model leading to equivalent circuit has also been derived for the purpose of steady-state performance analysis. The basis of the analysis is nodal admittance method as applied to the equivalent circuit.

Transient /dynamic behavior of grid-connected six-phase induction generator was analyzed for the operating mode /configurations such as:

- (i) When only one three-phase winding set is connected to grid and other winding set is open,

- (ii) When both the three-phase winding sets are connected to grid,

Steady-state performance analysis was carried out for the following operating mode configurations:

- (i) When one three-phase winding set is connected to grid and other winding set is open,
- (ii) When one three-phase winding set is connected to grid and other winding set is connected to resistive load,
- (iii) When both the three-phase winding sets are connected to grid,

In the analytical model (dynamic as well as steady-state), the effects of common mutual leakage reactance between the two three-phase winding sets have been included. The detailed analytical study was performed using MATLAB /SIMULINK.

Second part of the work deals with a proof-of-concept prototype, which was developed by modifying a conventional three-phase induction machine in such a way that it could be configured to operate at desired number of poles and phases. For the purpose of this work, test machine was reconfigured for six-pole, six-phase and six-pole, three-phase operation. The machine parameters for each configuration have been determined through no-load and blocked rotor test. The detailed experimentations have been conducted on each configuration to investigate the detailed steady-state performance of the grid-connected six-phase induction generator in different operating modes by mechanically coupling it to a cross-flow hydro turbine available in the laboratory. These configurations are:

- (i) When one three-phase winding set is connected to grid and other three-phase winding set is open,
- (ii) When one three-phase winding set is connected to grid and other three-phase winding set is connected to a constant resistive load,
- (iii) When both the three-phase winding sets are connected to supply grid,
- (iv) When both the three-phase winding sets are connected to supply grid along with reactive power compensation

Tests were also conducted on grid-connected three-phase induction generator for the following operating mode /configuration:

- (i) Three-phase winding connected to supply grid,
- (ii) Three-phase winding connected to supply grid along with reactive power compensation.

A comparative study of the performance indices for all the operating mode and configuration of grid-connected six-phase and three-phase induction generator was also made.