

## ABSTRACT

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In recent years, owing to the increased emphasis on renewable energy sources, development of suitable isolated power generators driven by energy sources such as wind, small hydro, biogas, etc. has assumed a great significance. With the renewed interest in wind turbines and micro-hydro-generators as an alternative energy source, the squirrel cage induction machine with capacitive self-excitation, known as self-excited induction generators (SEIGs) are being considered as an alternative to the well-developed synchronous generators. It is because of their lower unit cost, brushless rotor construction, absence of separate dc excitation source, rugged and robust structure, operational and maintenance ease, inherent protection against faults, good dynamic response and more over off-the-self availability. The induction generator's ability to generate power at varying speed facilitates its operation in various modes. These are as self-excited stand-alone (isolated) mode to supply far-flung and remote areas; in parallel with synchronous generator to fulfill the increased local power requirement and in grid-connected mode to supplement the real power demand of the grid by integrating from resources located at different sites.

In spite of SEIG having a number of advantages, it suffers from inherent poor voltage regulation, which is the result of gap between VARs supplied by shunt capacitors and VARs demanded by the load and machine. Furthermore, when the active power demand of the load is higher than the input rotor mechanical power, the load voltage collapses. These performance constraints of capacitively compensated induction generators limit their wide spread application, especially in situations where regulated load voltage and frequency are required.

Remedial measures such as the use of static reactive power generators and other power electronics based voltage regulating devices are costly and involve complicated control circuitry. Their operation causes switching harmonics and transients, thus discounts the very advantages of induction generator over synchronous generator for isolated applications. Therefore, the necessity of performance improvement at machine level is one of the prime aspects, which has diverted the research trend towards the multi-phase (phases in excess or three) machines.

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  $30^\circ$  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  $6K \pm 1$  ( $K = 1, 3, 5\dots$ ) 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.

Exhaustive literature surveys on multi-phase machine reports a large quantum of research activity are on the way expanding its universe for drive and control purposes. Improved reliability, magnetic flux harmonic reduction, torque pulsations minimization are the certain advantages due to which six-phase induction motors are beginning to be a widely acceptable alternative in high power applications. A distinct advantage of such machines is the absence of certain lower order space harmonics, which reduces a few unwanted power losses, and improves the power output along with its quality.

The research in this area is still in infancy, yet some extremely important findings have been reported in the literature indicating general feasibility of multi-phase system for stand-alone power generation. A poly-phase cage induction machine with double stator windings, one fixed and other able to be manually adjusted and positioned to match the mechanical and electrical power when used as a generator or a motor, is analyzed along with its feasibility in wind /hydro system. The generator scheme, based on the dual stator winding induction machine with displaced power and control three-phase winding wound for same number of poles is available where, one set of winding is responsible for electromechanical power conversion (i.e. driving the load) while the second one is used for purposes of excitation and control. This scheme underutilizes the full generating capability of dual stator winding induction generator, as the output of only one set of three phase windings is available for end use. Another one deals with the double stator induction machine with extended rotor common to both the stators. In all of these three cases, output is meant to feed the utility is only three-phase. The facts and scopes as mentioned above have motivated to facilitate the use of multi-phase induction generator in stand-alone isolated mode of operation, which could ensure a reliable supply of good quality. Induction generator in this configuration harnesses more output power in the same frame with better voltage regulation compared to its three-phase counterpart. Such

system for the power generation could also be made efficient and cost effective to compete with the other conventional sources of energy.

In view of the above, there is strong motivation to undertake a thorough and systematic investigation about the multi-phase (six-phase) self-excited induction generator so that the inherent advantageous features of multi-phase ac machine can be fully exploited. Hence, in order to utilize the potential application of multi-phase induction generator, investigations have been carried out with twin objectives. First one deals with the development of a new power generation scheme, where it is possible to supply two independent balanced or unbalanced three-phase load of utility from a single six-phase machine by shunting excitation capacitor bank either across a single three-phase set or across both three-phase winding sets of six-phase induction generator. Second objective explores the feasibility of multi-phase SEIG application in stand-alone small hydropower scheme to feed the three-phase utility /power grid via an interposed six to three-phase transformer with improved reliability. If one set of three-phase winding fails the other one may continue to feed the essential loads.

The first part of this thesis, therefore, presents the mathematical modeling of a saturated six-phase self-excited induction generator. 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 SEIG is based on two-axis ( $d-q$ ) model of the machine. A detailed analytical study under different operating conditions and loads was performed using MATLAB /SIMULINK.

Second part of this thesis 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 were determined through no-load and blocked rotor test. Synchronous speed test was also conducted to determine a suitable value of shunt capacitor to excite the machine for a suitable value of terminal voltage and winding current under the constraints posed by its rating. The detailed experimentation was carried out on each configuration to investigate the no-load as well as loading characteristics in different operating modes by mechanically coupling it to a hydro turbine available in the laboratory.

Experimental results regarding voltage and current build-up, loss of excitation and re-excitation, switching-in of resistive and resistive inductive load without and with short shunt series compensation has also been performed. Self-excitation under no-load condition and loading performance under a typical loading condition is elaborated with emphasis on variable speed operation of six-phase SEIG. It is found that some of the major problems like voltage collapse and situations that results total demagnetization regarding the operation of a three-phase SEIG are alleviated in six-phase SEIG. Experimental results obtained for the three-phase and six-phase self-excited induction generators, configured for different operating modes under different loading conditions, were compared to justify the suitability of six-phase induction generator over the three-phase counterpart. Finally, with known advantage of SEIG i.e. off-the-self availability, operational simplicity, excellent power quality and feasibility of optimum efficiency operation with better voltage regulation reflects the technical viability of six-phase induction generator for hydropower schemes.