ABSTRACT

The excessive use of conventional energy resources, especially, fossil fuels has resulted in increased energy cost, environmental pollution, global warming and green house gas emission. The fast depletion of fossil fuel energy resources and growing concerns of environment protection have led to large number of researches to develop eco-friendly renewable energy technologies.

Electrification of remote rural areas devoid of utility power supply is an important task for the sustainable development of a country. These far-flung, remote areas are characterized by sparsely distributed population with low electric load demand. Extension of existing national grid to such remote areas is not techno-economically feasible. But these un-electrified far-flung areas are blessed with sustainable renewable energy resources such as mini/micro hydro, wind, bio-mass etc. The electricity can be supplied to such remote and isolated areas through the development of autonomous, small-scale power generation system based on renewable energy. The self-excited induction generator (SEIG) has been found suitable for power generation from such renewable energy sources due to its advantages like simplicity, low cost, ruggedness, little maintenance, absence of DC, brushless etc. as compared to synchronous generator.

In remote and isolated areas, most of the electric loads are of single-phase type. Single-phase power supply is preferred over three-phase up to a load of 20 kW to make the distribution system simple and cost effective. Single-phase supply can be provided using single-phase induction motors as generators, but the single-phase induction machines are generally not available in the integral kW rating higher than 5 kW. Beyond this rating, the three-phase induction machines are inexpensive and more readily available with higher efficiencies as compared to single-phase machines of equivalent ratings. Due to these reasons, three-phase induction machines can be used for single-phase power generation up to a load demand of 20 kW. As the load increases beyond 20 kW, the three-phase supply using three-phase SEIG may be used. However, the use of three-phase SEIG for supplying single-phase loads is an extreme case of unbalanced operation that results in additional power loss, excessive heating, insulation stress and excessive vibrations in shaft. Under these conditions, a three-phase machine has to be de-rated in order to keep the temperature of the machine within allowable limits. In view of this, one is required to evaluate

maximum single-phase load that can be placed on the three-phase SEIG while maintaining the phase currents and voltages of the generator within the limits and as balanced as possible. Suitability of a SEIG scheme for supplying single-phase and/or three-phase loads over a allowable range of power is assessed by studying the steady-state and transient performance at practical operating conditions. A flat load characteristic is desirable in any generating system for efficient operation of a range of loads.

The transient performance analysis of C-2C scheme of single-phase power generation using a three-phase delta-connected induction machine where the capacitors C and 2C are connected in parallel with two stator windings of the SEIG and the load is connected across the capacitor C is reported in the literature. This scheme has good power output i.e., more than 80 % of the three-phase rating of the machine with unity pf load. But the voltage regulation is very poor and the de-excitation of the SEIG occurs due to short-circuit at load terminals. With the capacitors corresponding to maximum output power, there is over voltage across the windings of the generator at no-load condition, which is not desirable. This scheme is particularly suitable for single-point operation with load controller. Where as another important scheme i.e., shunt and series capacitor excitation scheme (C_{sh}-C_{se} scheme) using three-phase delta connected induction machine for generating single-phase power, where the capacitor C_{se} is connected in series with the load and the capacitor C_{sh} is connected across the lagging winding of the SEIG exhibits very good voltage regulation. It has also maximum power output more than 80 % of the three-phase rating of the machine. But the dynamic behavior of the SEIG using C_{sh}-C_{se} scheme during different transient conditions is not reported in the literature that requires further investigation.

In India, the normally available small rating three-phase induction machines are rated for 415 V. The single-phase power supply is provided at the voltage range of 220-240 V. The problem with three-phase 415 V delta connected induction machine used as single-phase SEIG is that it can not supply single-phase power in the voltage range of 220-240 V. The output power can be supplied at the voltage range of 415 V (i.e., the phase voltage of the delta connected machine), which is not suitable for residential load applications. In that case, if a three-phase, 415 V, star connected induction machine is reconfigured in delta mode and used in C_{sh}-C_{se} scheme, the single-phase output voltage at 220-240 V range, suitable for household appliances may be available. This problem may also be overcome by using a star connected, three-phase, 415 V induction machine for generating single-phase power, suitable for home appliances, with three capacitors (C_p-C_s scheme), C_p and two C_s's, where the capacitor C_p is connected in parallel with the load and the two series capacitors C_s's are connected in series with the two windings of the SEIG with the common point of the two series capacitors connected to one terminal of the load. Only, the steady-state performance of this scheme is available in the literature. Hence, the transient behavior of the SEIG using C_p-C_s scheme needs to be investigated. Since the single-phase induction motors are widely used in household applications, the suitability of the above configurations for supplying dynamic load i.e., induction motor loads have to be searched out. More over, the minimum and maximum values of capacitances need to be determined for self-excitation of the SEIG and to maintain the excitation while loading the SEIG. Accordingly, the main objectives are listed below:

(i) Detailed investigations on the suitability of the above two schemes i.e., C_{sh}-C_{se} scheme for three-phase delta connected induction machine and C_p-C_s scheme for star connected induction machine for supplying single-phase power suitable for residential load applications need to be carried out.

(ii) Design and development of single-phase load controller.

(iii) Since beyond 20 kW load, three-phase supply is provided with three-phase SEIG, vector control technique for SEIG application need to be investigated in detail with different kinds of loads for improved dynamic performance and phase balance even with unbalanced loads.

In view of the above facts, the analyses of transient behavior of C_{sh}-C_{se} and C_p-C_s schemes have been carried out in this thesis considering resistive, inductive and dynamic loads. The steady-state performance analysis of these two schemes with resistive and inductive loads has also been carried out using steady-state models and compared with the performance computed from the dynamic model at steady-state. Moreover, the performances of these two schemes with forward and reverse rotations of the SEIG have been investigated. The reverse rotation in C_{sh}-C_{se} scheme keeping the load and the series capacitor connected across the same phase as with forward rotation is not allowable, since the current in the stator winding across which the shunt capacitor is connected, always remains above the rated value. But reconnecting the load and the series capacitor across the other phase except the winding across which the shunt capacitor is connected, the similar performance as with forward rotation is achieved. In C_p-C_s scheme, the output power remains almost same during reverse rotation, only the stator phase currents are interchanged in the two phases with which the series capacitors are connected.

The minimum capacitance requirement for self-excitation of the SEIG has been determined by eigenvalue analysis technique and also from steady-state model of the generator configuration considering constant speed of the prime-mover. In C_{sh}-C_{se} scheme, a hybrid variable dynamic model of the induction machine has been developed considering stator phase currents in three-phase a-b-c variables and rotor currents as d-q variables. In case of hybrid model, the inverse transformation to obtain the a-b-c variables from d-q variables is not required, since the stator variables remain as a-b-c variables. In case of C_p-C_s scheme, the induction machine has been modeled in d-q axes stationary reference frame with d-q axes stator and rotor currents as state variables incorporating the effect of cross-saturation. The first order differential equations of the dynamic model are solved using the fourth order Runge-Kutta numerical integration technique. In steady-state model, the closed loop impedance is minimized by the Sequential Unconstrained Minimization Technique (SUMT) in conjunction with Rosenbrock's method of rotating coordinates. The experimentation of C_{sh}-C_{se} scheme has been carried out using two induction machines – (i) a three-phase, 415 V, 7.4 A, delta connected induction machine and (ii) a three-phase, 2.2 kW, 415 V, 4.5 A, star connected induction machine reconfigured in delta mode. Similarly, a three-phase, 2.2 kW, 415 V, 4.5 A, star connected induction machine has been used for experimentation in C_p-C_s scheme. A 1 hp, 230 V, 6 A, single-phase induction motor is used as dynamic load. The simulated results of transient and steady-state analyses are compared with the experimental results to validate the developed models. Both these two schemes have good voltage regulation and the SEIG does not lose excitation during short-circuit at load terminals but continues to feed the fault current. Further re-excitation takes place after the clearance of the short-circuit fault. The maximum power output of C_p-C_s scheme is low (around 35 % of the three-phase rating of the machine), where as, that of C_{sh}-C_{se} scheme is around 80 %.

The transient behavior and dynamic stability of the SEIG can also be predicted using dynamic eigenvalue analysis. Accordingly, dynamic eigenvalue analysis technique has been used in C_p-C_s scheme for resistive load to determine the transient behavior of the SEIG during voltage build-up at no-load, load perturbation and short-circuit conditions. The movements of the system eigenvalues have also been identified to determine the dynamic stability of the system.

The literature reveals that the maximum output power of C_p-C_s scheme is very low (i.e., around 35 %) as compared to the three-phase rating of the SEIG. Since, the maximum output power of a SEIG depends on the machine parameters and other factors such as value of the capacitor, speed etc., their values should be properly selected for efficient utilization of the power generation scheme. As the variation of speed is not always possible, the algorithms have been developed for determination of optimal capacitors for maximum output power of C_p-C_s scheme considering resistive, inductive and capacitive loads. The maximum powers are obtained as 45 % to 50 % of three-phase rating of the machine for resistive load depending on the rating of the machine, 44.5 % for inductive load of 0.8 pf and 33.2 % for 0.8 pf capacitive load. The variation of maximum output power for different power factor loads have been studied. The developed algorithms are validated through experimentation.

Apart from a number of advantages, the SEIG suffers from inherent problems of poor voltage and frequency regulation. The poor voltage regulation is the result of gaps between VARs supplied by the capacitors and VARs demanded by the load and the machine. In micro-hydro applications, the use of governor is not an economical option due to its cost and operational maintenance, and therefore the load controller can be used to overcome such problems. Moreover, for maximum power output using C_p-C_s scheme with acceptable output voltage, the SEIG needs single-point operation, which is possible with the load controller. Accordingly, a single-phase electronic load controller has been designed and developed. Its performance with C_p-C_s scheme has been investigated considering resistive, inductive and dynamic main loads. For simulation, SIMULINK based model of this scheme (i.e., SEIG including the load controller) has been developed. The simulated results of the transient analysis have been compared with the experimental results to validate the developed models.

Since, the load characteristic of the three-phase SEIG is drooping in nature, i.e., the output voltage reduces with increase of load, capacitive VAR should be added with varying load in order to keep the terminal voltage within acceptable limits. A controller based on “scalar control methods” cannot achieve the best performance during transients. The field oriented control or vector control has permitted the development of high performance variable speed generation systems. Very little information on the application of vector control technique for control of induction generator is available in the literature. Vector control technique for induction generator application needs to be further investigated. Accordingly, the direct, indirect and sensorless vector control techniques for stand-alone induction generators have been simulated to study the feasibility of the control scheme. The space-phasor model of the induction machine has been used in simulation. The main advantage of space-phasor model is that the system reduces to a two winding system like the DC machine – hence the apparent similarity of them in control to obtain a decoupled independent flux and torque control as in the DC machine. The simulations are carried out in MATLAB/SIMULINK environment considering DC load as well as AC resistive, inductive and dynamic loads. For DC load and AC resistive and inductive loads, one three-phase, 2.2 kW, 415 V, 4.5 A induction machine is used as SEIG, where as for dynamic load, the analysis is carried out considering one three-phase, 7.5 kW, 400 V, 15.13 A induction machine as SEIG and the above 2.2 kW induction machine as a dynamic load. In case of DC load, and AC resistive and inductive loads, the performances of the SEIG under different transient conditions such as self-excitation at no-load, sudden application of load, and load perturbation have been investigated. For dynamic load, the performances of the SEIG due to sudden switching of motor load on the SEIG terminals, sudden application and removal of mechanical load on the motor have also been investigated.

A comparative study of direct, indirect and sensorless vector control techniques have been carried out. All these algorithms show very fast response. The direct vector control (DVC) is less sensitive to parameter variations. It is dependent only on stator resistance but does not work properly at low speed operation. Where as, indirect vector control (IVC) can work in wide variation of speed from zero to field weakening region. For induction generator applications, DVC seems to be a more effective approach because zero speed operation is not required. Further, to reduce the cost of the system, sensorless vector control technique has been investigated in detail. It shows similar performance like DVC.

The investigations carried out in this thesis on analysis of C_{sh}-C_{se} and C_p-C_s schemes for single-phase power generation; determination of optimal capacitors for maximum power output of C_p-C_s scheme; development of single-phase electronic load controller with C_p-C_s scheme and vector control technique for three-phase SEIG, bring the basic objectives of this thesis to a successful conclusion. Investigation on three-phase, 415 V, star connected induction machine reveals that the C_p-C_s scheme can supply single-phase power at the voltage range of 220-240 V suitable for household appliances. Where as the output power from the C_{sh}-C_{se} scheme using a three-phase, 415 V delta connected induction machine is available in the voltage range of 415 V, which is not suitable for residential load applications. This problem can be solved by reconfiguring a 415 V, star connected induction machine in delta and using in C_{sh}-C_{se} scheme, where the output power can be supplied at the voltage level of 220-240 V. In case of C_p-C_s scheme, the output power is less as compared to C_{sh}-C_{se} scheme. But at no-load or lower load in C_{sh}-C_{se} scheme, the voltage and current in the phase winding of the SEIG across which the shunt capacitor C_{sh} is connected exceeds the rated values. From the study, it is concluded that a three-phase, 415 V, delta connected machine is not suitable for supplying single-phase power required for home appliances. However, a three-phase, 415 V, star connected machine can be used in both the configurations (i.e., C_p-C_s scheme and C_{sh}-C_{se} scheme after reconfiguring in delta) for single-phase power generation suitable for residential load applications. In case of three-phase SEIG, further investigation on the use of combined direct and indirect vector control techniques for variable speed wind turbine applications may be carried out.