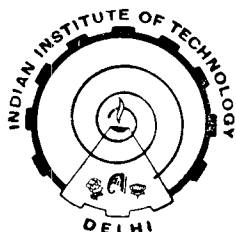


INVESTIGATIONS OF THE PHENOMENON OF CAPACITOR SELF-EXCITATION IN INDUCTION MACHINES AND ITS APPLICATIONS

by
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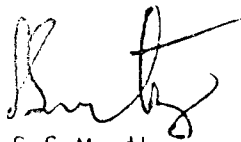
to

MY PARENTS

who always showed me right path

CERTIFICATE

Certified that the thesis entitled
"Investigations of the Phenomenon of Capacitor
Self-excitation in Induction Machines and Its Applications"
which is being submitted by Mr. A.K. Tandon, in partial
fulfilment for the award of the Degree of Doctor of
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of Technology, Delhi, is a record of the student's own work
carried out by him under our joint supervision and guidance.
The matter embodied in this thesis has not been submitted
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(Ajay Kumar Tandon)

SUMMARY

An externally driven 3 phase induction motor will generate e.m.f. in its windings if a three phase capacitor bank of sufficient value is connected across its terminals. The e.m.f. so produced keeps on rising till its value gets arrested due to the magnetic saturation in the machine. This voltage continues to exist as long as the appropriate values of speed and the capacitance are maintained. This phenomenon is termed as capacitor self-excitation of an induction machine, as the capacitor provides the excitation requirement of the machine.

Capacitor self-excitation can be used as a desirable feature in certain applications such as (i) self-excited induction generator, and (ii) dynamic braking of induction motors. Thus the study of the self-excitation in induction machines becomes important for its satisfactory exploitation toward these applications. Though the existence of this phenomenon has been recognised in earlier literature, not much work has so far been reported on the detailed study of the phenomenon and its applications. The present thesis, apart from dealing with the general study of the capacitor self-excitation phenomenon, includes investigations of this phenomenon and its applications, as mentioned above.

A capacitor self-excited induction generator offers certain advantages over a conventional synchronous generator as a source of isolated power supply. Reduced unit cost, brushless rotor (squirrel cage construction), absence of a separate d.c. source and ease of maintenance are among the advantages. Due to changed emphasis on energy problems the development of suitable isolated power generators driven by unconventional energy sources such as wind, biogas, etc., has assumed greater importance. The development of static power converters facilitate control of self-excited generators in terms of output voltage and frequency. It may be mentioned that the conventional induction generator can be used only in the presence of a grid. However, capacitor excitation makes the use of induction machine for power generation even at isolated locations. Recently, isolated small hydro power stations have been thought of as viable supplements to meet the growing energy requirements in many countries including India. However, these hydro potentials are available in isolated and remote regions away from the grid. In such cases capacitor excited single unit induction generators would be ideal to satisfy economically the local needs of energy. Not much work has so far been reported on the analysis and application of such induction generators. Analysis of these generators is of paramount importance from design as well as operational point of view. Knowing the parameters of the machine it should be possible to determine its performance

for given capacitance, speed and load conditions. Available literature mainly deals with induction generators whose terminal voltage/frequency are known. In this thesis analytical techniques are developed to predict the performance of a self-excited induction generator for any speed, load and capacitor condition when the voltage and frequency are not known.

The braking of three phase induction motors used in industrial drives has been a topic of considerable interest over many years. Plugging, regenerative braking and d.c. injection braking are methods already dealt with in the literature quite elaborately. Braking can however, also be accomplished through the use of capacitor self-excitation. If the supply of a three phase induction motor is disconnected and simultaneously a balanced three phase capacitor bank of sufficient value is connected across the motor terminals large voltage and currents will be induced in the motor windings. The electrical losses so produced are dissipated in stator/rotor windings quickly, ~~dissipating~~ the kinetic energy of the motor and producing a braking torque.

Braking through capacitor self-excitation using three phase balanced capacitor bank is already found in literature. A few schemes using this mode of self-excitation in conjunction with other methods have also been suggested. Braking using single phase self-excitation is also possible and proves to be a superior and simple method of braking.

Hardly any reference is available in literature on the capacitor braking using single phase mode of self-excitation. Emphasis has therefore been laid on the single capacitor braking in the present work. The attention has been mainly focused on the development of a suitable multistage braking system based on the single phase self-excitation combined with other methods.

The present investigation has been carried out in three phases. The first phase deals with the general study of the phenomenon of self-excitation. Voltage building being a transient process, relevant dynamic model needs to be established for proper understanding of the system. Such models have been established for the cases of single phase as well as three phase self-excitation separately. An analytical procedure has been outlined to examine whether self-excitation would be possible under a given condition of speed, capacitance value, type of connection and the machine parameters. Suitable dynamic equations using operational equivalent circuits are formulated, which resulted in characteristic equation, whose roots determine the existence of self-excitation. Computer algorithm for finding minimum capacitance required to cause self-excitation at any particular speed has been a useful outcome of this study, which is used in the later part of the investigation. Theoretically predicted results compared well with those obtained experimentally. Based on this experience a series of

design curves are presented in per unit values for a range of ratings of machines, which could help in choosing proper values of capacitors for any machine.

Next part of the thesis deals with the study of self-excited induction generators operating under steady state, with three phase capacitor bank connected across the terminals. Model equations for no load, resistive load and lagging reactive loads have been derived with a view to determine complete steady state performance of such a generator under these conditions.

The analysis of a capacitor self-excited induction generator poses problem due to the uncertain level of magnetic saturation in the machine and its effect on the machine parameters. In the present analysis only the magnetising reactance, x_m is considered to be dependent on saturation. With the help of the "synchronous speed test" a curve showing the variation of x_m with air gap flux (which is proportional to V_g/F where V_g is the air gap voltage, and F is the p.u. frequency) is obtained.

Three methods have been developed for the steady state analysis of such generators under different loading conditions. In all the three methods the level of saturation under steady state was identified by determining the value of saturated magnetising reactance at load conditions. The methods also give the p.u. frequency 'F' of the generated

voltage under those conditions. Having determined x_m and F , the air gap voltage V_g was determined from x_m Vs, V_g/F curve. The relation between x_m & V_g/F was expressed in a linearized form over the operating range and the data was stored in the programme for required computation. Having determined V_g and F , the complete performance i.e. the terminal voltage, the currents in stator/rotor, capacitor current, load current, power input and efficiency were determined directly from the standard phasor equivalent circuit.

The first method uses the so called "complex frequency approach" wherein a characteristic polynomial was formulated. Zeros of this polynomial were computed (through a computer subroutine) for given values of 'C' and the machine parameters, as different values were assigned to x_m . The value of x_m which caused the real part of any one of the zeros to acquire zero value is the value of the magnetising reactance the machine would attain under steady operation. Imaginary part of this root gives the per unit frequency F of self-excitation. In the second method an equation in terms of x_m and F with complex coefficients as obtained through the steady state phasor equivalent circuit was formulated. Separating real and imaginary parts yielded two simultaneous non linear algebraic equations in x_m and F which were solved by Newton-Raphson method. The third method also uses a steady state approach by recognising the fact that the equivalent impedance as viewed from the terminals of ' x_m ' is imaginary. This fact has been exploited

(x)

to obtain equations in ' x_m ' and 'F' separately. A subroutine was used to compute the value of F by solving a 5th order algebraic equation with one unknown (i.e. F). x_m was then computed corresponding to this value of F. A comparison of all three methods is also presented in the thesis with a view to assess their computational requirements.

Extensive experimentation has been carried out on different induction machines (educational as well as industrial type) and the predicted steady state performance has been found to be in close agreement with the measured values.

Families of characteristics showing the effect of various system parameters are presented. As these curves are presented using p.u. values, they may provide guidelines for appropriate design of the system. It has been observed that while small changes in stator resistance and leakage reactance do not affect the performance, the rotor resistance, magnetising reactance, speed and terminal capacitor are found to be very sensitive in determining the terminal voltage and frequency in addition to their variation with load. Since the basic requirement of a generating unit is to keep the variation in voltage/frequency with load within a prescribed limit, the analytical methods developed here would be very useful in designing suitable voltage regulating systems. Range of capacitance variation required to maintain constant voltage at all loads for typical machines are determined.

The final phase of the thesis deals with the application of self-excitation phenomenon for braking of three phase induction motors. Salient features of such type of braking have been highlighted which include certain limitations too. Whereas economy as regards the braking power, low loss, and effectiveness at highest speed are the advantages, ineffectiveness at lower speeds and generation of large voltage and current transients in case of excessively large value of capacitance are found to be the main drawbacks of this type of braking. In the process of seeking a compromise between the various factors, a very effective multistage braking scheme has been evolved. Initially a single capacitor is connected across two of the terminals of a star connected motor allowing single phase self-excitation to be produced. Following a certain quick speed drop a second capacitor is added in parallel with the first to sustain the self-excitation and further reduce the speed. In the third step magnetic braking is achieved by short circuiting the third terminal with one of the first two terminals. Finally, the motor is brought to stand still by a minor d.c. injection. In designing the values of capacitors at different stages, the results regarding the minimum capacitance requirement to cause self-excitation at different speeds presented in the initial part of the thesis have been used. Various switchings are accomplished through triacs fired by suitable electronic delay circuits using ICs. A complete prototype of multistage braking control system has been fabricated and successfully demonstrated to brake a 2.9 hp 4-pole induction motor within a fraction of a second. This scheme is expected to be very useful in many industrial drive applications where quick and frequent braking operations are required.

A series of experiments have been performed with the novel multistage braking system to determine various transients during the braking period in order to assess the suitability of windings and capacitor system. The effect of capacitor values on initial rate of fall in speed, the braking time and the peak transients of voltages and currents has been studied. This would help in choosing suitable values of capacitors, and the time delays between different stages of switching. Braking performance under this scheme is compared with that under normal d.c. injection method. Typical experimental recordings are presented and discussed.

The major contributions of the present investigation can thus be summarised as follows:-

1. Suitable mathematical models for analysis of both single phase and three phase self-excitation conditions have been developed. Techniques are used to determine capacitor values for self-excitation at different speeds which are verified by extensive experimentation.
2. Accurate analytical techniques for analysing the self-excited induction generators have been developed. Three methods of analysis are formulated and the corresponding computer algorithms have been developed.
3. Taking the parameters of a laboratory machine, its performance as a self-excited induction generator has been computed for different capacitor and load conditions.

Theoretical results are found to match closely with those found experimentally. A comparison of various analytical methods developed is made in respect of the computational requirements.

4. Effects of variation of a number of system parameters on the performance of a self-excited induction generator have been studied with a view to facilitate proper designing of the machine and associated systems to work suitably as an independent generating system.
5. The feasibility of using a conventional motor as a self-excited generator has been studied, keeping in view the problems faced by the manufacturers in affecting major changes in design.
6. A novel multistage dynamic braking system using single phase graded capacitor self-excitation in conjunction with other methods have been developed, fabricated and tested. This has made it possible to brake a motor within a fraction of a second.
7. Various features including the advantages and disadvantages of this system have been compared with the widely prevalent d.c. injection braking.
8. Extensive experimentation is performed on the multistage braking system and results in the form of transient patterns under braking are presented to give certain useful criterion for selection of various system parameters with a view to designing a suitable braking system for different motors.

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