ELECTRIC DRIVES SUITABLE FOR FLYWHEEL ENERGY STORAGE SYSTEMS

by

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A C K N O W L E D G E M E N T

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CR. ANBARASU

C E R T I F I C A T E

Certified that the thesis entitled, "Electric Drives suitable for Flywheel Energy Storage Systems", which is being submitted by Mr. R. Anbarasu, in fulfilment for the award of the degree of Doctor of Philosophy in Electrical Engineering of the Indian Institute of Technology Delhi, is a reward of the student's own work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

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ABSTRACT

Considerable amount of research and development work is being carried out in many countries to evolve fuel efficient vehicles. Towards this objective investigations are being carried out in a number of areas such as electronic fuel injection systems, modifications in compression ratio of IC Engine etc. One such area is the recovery and utilization of kinetic energy wasted in brakes. Such a recovery of energy is expected to give fuel saving of the order of 30% to 40% mainly for vehicles operating in city environment. Basically, the recovered energy can be stored (a) in batteries in the form of chemical energy, (b) in compressed fluid (c) in rotating high-speed flywheels in the form of kinetic energy. Of these, flywheel energy storage system is thought to be the most promising. The work reported in this thesis deals with some aspects of the drive system required for a hybrid vehicle using flywheel energy storage.

In a hybrid vehicle, using flywheel as an energy storage unit, there are two electrical drive units. One is coupled mechanically to the flywheel. The other is connected mechanically to the IC engine and the driving wheels through drive line components such as gears and clutches.

One of these drive line units,operates as a motor and the other as a generator at any one time. For example, during braking (bringing the vehicle to standstill) the machine connected to the wheels (the traction machine) operates as a generator and feeds the energy to the second machine (the flywheel machine) coupled to the flywheel. As a result, the speed of the flywheel increases. When the vehicle is started from standstill condition, the machine connected to the flywheel generates and feeds the other machine which operates as a motor. It will be seen that during the energy transfer the speed of the machine, which supplies energy, keeps decreasing and the speed of the machine, which receives energy, keeps increasing. The voltage generated by the machine whose speed is decreasing has to be higher at all times than the back emf of the machine whose speed is increasing. Such a requirement puts severe constraints on the controllers which have to maintain suitable voltage levels for the required energy transfer to take place.

In order to recover the major portion of the kinetic energy, the machine connected to the engine must develop sufficiently high voltage even at low speeds. The machine connected to the flywheel has to operate at very high speeds of the order of 12000 rpm to 24000 rpm. This machine may have to operate under partial vacuum. Thus, electrical machines are required to work as variable speed motor/generator, and be amenable to control of terminal voltages. The machines are required to be highly efficient, compact, reliable and economical. Whilst the dc shunt machine is the best suited for variable speed operations, the speed range is limited due to the presence of mechanical commutator. The work in this thesis was an attempt to develop the required hybrid drive using synchronous machines. In the motoring mode,the system proposed was a synchronous machine fed by a line commutated inverter. Though such a motor does not have a self starting capability, this problem is not insurmountable in practice.

In this investigation a low-speed (traction) synchronous machine using commonly available stamping was designed and fabricated considering all stringent operating conditions of the machines mentioned above. A low value of air gap flux density was selected while designing the machine in order to accomplish a higher efficiency. The desired value of voltage (high) was obtained by having a higher number of armature winding turns for a given frame size of the machine. In fact, it was found that the designed machine did not deliver the desired levels of voltage and current(hence power output) because of the higher values of armature reactance. The armature reaction could not be compensated by increasing field ampere turns because of space limitation for accommodating higher number of turns in the rotor. Therefore, in this investigation an attempt was made to compensate the armature reaction by using external passive networks. These networks were comprised of passive components such as capacitors, saturable reactors etc. By using appropriate networks, voltage-ampere characteristics similar to dc shunt machine were realised.

It was found that this machine could not be operated as line-commutated inverter fed motor satisfactorily. With the use of compensating networks, it was possible to operate the machine as a motor over a wide operating speed (300 rpm to 1000 rpm) range. It was found that the desired (i) level of power output over a wide speed range, and (ii) voltage-ampere characteristics (hence speed-torque characteristics), could be obtained by optimising th network components.

A high-speed (flywheel) synchronous machine, was also designed and fabricated. It was designed for the maximum operating speed of 6000 rpm. The ratio of the armature reactance to no-load voltage was low as compared to that of the low-speed (traction) machine. Hence, the flywheel machine was found to operate satisfactorily as a variable speed generator , as well as line commutated inverter fed motor. It was also found that with the use of compensating networks the performance of the machine improved in terms of power output and voltage levels.

An analytical model was developed for predicting the performance of the synchronous machines with the compensating networks. In this model the non-linearity of the saturable reactor was incorporated. It was found that the predicted results had a good qualitative as well as quantitative agreement with the measured values.

The possibility of using squirrel cage induction machines, as a drive, for hybrid vehicle application was also investigated. It was realised that the induction machine has to be operated as self (or capacitor) excited induction generator. A suitable network comprising of the capacitor and the saturable reactor was developed for the purpose of varying the output voltage level over a wide range. Variable speed operation of induction motor fed from a line commutated inverter was also accomplished. These aspects were verified experimentally.

CONTENTS

CHAPTER 4 PERFORMANCE OF TRACTION (LOW-SPEED) MACHINE AS GENERATOR WITH RESISTIVE LOAD AND BACK EMF LOAD