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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

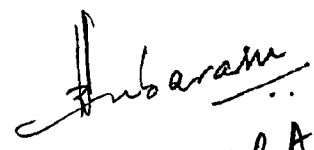
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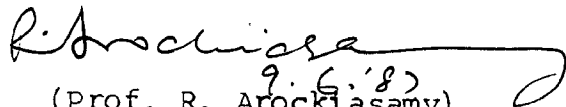
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C.R. ANBARASU

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.


9.6.82
(Prof. R. Arachisara)

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 the 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

	Page
LIST OF SYMBOLS	xvii
ABSTRACT	xxiv
CHAPTER 1 INTRODUCTION	1
1.1 A Typical Hybrid Vehicle Scheme	3
1.2 Major Aim of the Investigations	17
1.3 Outlines of Chapters	19
1.4 Experimental set-up	20
CHAPTER 2 ANALYSIS OF HYBRID VEHICLE SYSTEM	
2.0 INTRODUCTION	23
2.1 Energy and Power Requirement of an Urban Transport	23
2.1.1 Acceleration energy	26
2.1.2 Energy for cruising	26
2.1.3 Effect of number of stops per mile on total energy consumption	27
2.1.4 Power requirement during accele- ration	27
2.1.5 Cruise power	27
2.2 Fuel Consumption of a Conventional Vehicle over a City Driving Cycle	29

2.3	Kinetic Energy (KE) Possessed by a Vehicle	33
2.4	Comparison of Fuel Consumption of Conventional and Hybrid Vehicle Systems	36
2.5	Methods of Improving Fuel Saving in Hybrid Vehicle Scheme	42
2.5.1	Load sharing concept	43
2.6	Selection of Hybrid Vehicle System Components	48
2.6.1	Selection of flywheel	48
2.6.2	Selection of flywheel machine	56
2.6.3	Selection of Traction machine	58
2.6.4	Selection of engine	59
2.6.5	Selection of gear box	60
2.6.6	Selection of clutch	60
2.7	Conclusion	61

CHAPTER 3

DESIGN AND DEVELOPMENT OF LOW-SPEED
(TRACTION) AND HIGH-SPEED (FLYWHEEL)
SALIENT POLE SYNCHRONOUS MACHINES

3.0	INTRODUCTION	62
3.1	Design Details of Low-Speed (Traction) and High-Speed Flywheel Machines	65

3.1.1	Stator and rotor stampings	65
3.1.2	Stator winding design	73
3.2	Magnetic Circuit Calculations	73
3.3	Rotor Winding Design	77
3.4	Theoretical Calculation of Machine Parameters	78
3.4.1	Direct and quadrature axis reactances	80
3.4.2	Leakage reactance of armature winding	81
3.5	Performance Characteristics	85
3.5.1	Open circuit characteristics	85
3.5.2	Short circuit characteristics	87
3.6	Measurement of Machine Parameters	91
3.6.1	DC resistance of stator winding	91
3.6.2	Direct axis armature reactance	91
3.6.3	Quadrature axis armature reactance	92
3.6.4	Leakage reactance measurement	92
3.6.5	Negative sequence reactance	93
3.7	Calculation of Stator Core Loss	94
3.8	Conclusion	97

CHAPTER 4	PERFORMANCE OF TRACTION (LOW-SPEED) MACHINE AS GENERATOR WITH RESISTIVE LOAD AND BACK EMF LOAD	
4.0	INTRODUCTION	98
4.1	Analysis of Synchronous Machine	99
4.1.1	Phasor diagram of salient pole synchronous machine	102
4.2	Experimental Set-Up	103
4.3	Performance of Traction (Low-Speed) Generator with Resistive Load (Case A)	105
4.3.1	Analysis	105
4.3.2	Performance characteristics	107
4.4	Methods of Compensating Armature Reaction in Synchronous Machines	112
4.5	Performance of Traction (Low-Speed) Generator with Series Capacitor as Armature Reaction Compensating Network (Case B)	112
4.5.1	Analysis	112
4.5.2	Performance characteristics	116
4.6	Operation and Performance of Traction (Low-Speed) Generator	125

	with AC Saturable Reactor (SR) and Series Capacitor Compensating Network (Case C)	
4.6.1	AC saturable reactor	125
4.6.2	Operation of saturable reactor (SR) with Series linear inductor	126
4.6.3	Waveforms of voltage, and current of a salient pole synchronous generator connected with ac saturable reactor	129
4.6.4	Analysis of traction (low-speed) generator with case C compensat- ing network (Case C)	133
4.6.5	Experimental results	141
4.7	Performance of Traction (Low-Speed) Generator with Shunt Capacitor as Compensating Network (Case D)	147
4.7.1	Performance characteristics	150
4.8	Performance of Traction (Low-Speed) Generator with Shunt AC Saturable Reactor and Capacitor Combination as Compensating Network (Case E)	153

4.8.1	Analysis	155
4.8.2	Performance characteristics	155
4.8.3	Experimental results	158
4.8.4	Discussions on waveforms	160
4.9	Performance of Traction (Low-Speed) Generator with Series and Shunt Combination Compensating Network (Case F)	165
4.9.1	Analysis	165
4.9.2	Performance characteristics	167
4.9.3	Experimental results	175
4.10	Operation of Traction (Low-Speed) Generator with Rectifier-Line Commutated Inverter(LCI) Combination as Load	175
4.10.1	Experimental Set-up	177
4.10.2	Analysis	179
4.11	Performance of Traction (Low- Speed) Generator with Case B Network and Back emf Load	180
4.11.1	Discussion on experimental and theoretical results	182
4.11.2	Discussions on waveforms	182

4.12	Performance of Traction (Low-Speed) Generator with Back emf Load and Case E Network	184
4.12.1	Performance characteristics	184
4.12.2	Discussion on waveforms of voltage and current	184
4.13	Performance of Traction (Low-Speed) Generator with Case F Network and Back emf Load	190
4.13.1	Performance characteristics	190
4.13.2	Discussion on waveforms of voltage and current	190
4.14	Conclusion	197
CHAPTER 5	OPERATION AND PERFORMANCE OF LOW- SPEED MACHINE AS LINE COMMUTATED INVERTER (LCI) FED SYNCHRONOUS MOTOR(SM)	
5.0	INTRODUCTION	199
5.1	General	200
5.2	Analysis of LCI Fed Synchron- ous Motor	204

5.2.1	Performance equations of line commutated inverter (LCI)	205
5.2.2	Performance equations of synchronous motor	212
5.2.3	Expressions relating parameters of synchronous machine and LCI	215
5.2.4	Commutating reactance	216
5.2.5	Commutation voltage	217
5.2.6	Commutation failure of LCI-SM	218
5.2.7	Method of determining the performance of LCI-SM at constant speed	218
5.2.8	Determination of commutation failure and P_{out} of LCI-SM	220
5.3	Performance Characteristics of Low-Speed LCI-SM (Analytical): Case A	221
5.3.1	$V_L - I_L$ characteristics	222
5.3.2	$P_{out} - I_L$ and $T - I_L$ characteristics	225
5.3.3	Effect of overlap angle (μ)	228
5.4	Experimental Set-Up	234
5.4.1	Experimental results of designed low-speed LCI-SM	236
5.4.2	Experimental results of a laboratory machine	238

5.5	Operation of Low-Speed(Traction) LCI-SM with Armature Reaction Compensating Network	241
5.6	Performance of Low-Speed(Traction) LCI-SM with Case B Network (or Case B)	241
5.6.1	Performance equations	241
5.6.2	Performance characteristics	245
5.6.3	Experimental observations	253
5.6.4	Computation of overlap angle (μ) of LCI-SM with Case B Network	254
5.7	Performance of Low-Speed LCI-SM with Case C Network (Case C)	257
5.7.1	Performance equations	259
5.7.2	Performance characteristics	262
5.8	Performance of Low-Speed LCI-SM with Case D Network (or Case D)	272
5.8.1	Performance equations	272
5.8.2	Performance characteristics	274
5.8.3	Effect of shunt capacitor on commutation of LCI	279
5.9	Performance of Low-Speed LCI-SM with Case E Network (or Case E)	281
5.9.1	Performance equations	282
5.9.2	Performance characteristics	284

5.9.3	Experimental results	285
5.9.4	Discussion on recorded waveforms	298
5.10	Performance of Low-Speed Machine as LCI-SM with Case F Network (Case F)	301
5.10.1	Performance equations	302
5.10.2	Performance characteristics of LCI-SM with case F network at constant speed	305
5.10.3	Experimental results	311
5.10.4	Discussion on measured torque-speed characteristics	315
5.11	Conclusion	320
CHAPTER 6	PERFORMANCE OF HIGH-SPEED (FLYWHEEL) MACHINE AS GENERATOR AND AS LINE COMMUTATED INVERTER FED SYNCHRONOUS MOTOR (LCI-SM)	
6.0	INTRODUCTION	322
6.1	Performance of High-Speed (Fly- wheel) Machine as Generator with Resistive Load	323
6.1.1	Performance of high-speed (flywheel) machine as generator with resistive load (case A) (theoretical)	323

6.1.2	Performance of high-speed generator with case B network and resistive load(theoretical)	329
6.1.3	Performance of high-speed generator with case C network and resistive load (theoretical)	335
6.1.4	Performance of high-speed generator with case D network and resistive load (theoretical)	341
6.1.5	Performance of high-speed generator with case E network and resistive load (theoretical)	343
6.1.6	Performance of high-speed generator with case F network and resistive load (theoretical)	347
6.2	Performance of High-Speed (Flywheel) Machine as Line Commutated Inverter (LCI) Fed Synchronous Motor (SM)	349
6.2.1	Performance of high-speed (flywheel) machine as LCI-SM without compensating network case A (theoretical)	351
6.2.2	Experimental results of high-speed (Flywheel) LCI-SM	357

6.3	Performance of High-Speed (Flywheel) Machine as LCI-SM with Case B Network (or Case B) (Theoretical)	362
6.3.1	Performance characteristics at constant speed	362
6.4	Performance of High-Speed(Flywheel) Machine as LCI-SM with Case C Network (or Case C) (Theoretical)	370
6.4.1	Performance characteristics at constant speed	370
6.5	Performance of High-Speed (Flywheel) Machine as LCI-SM with Case D Network (or Case D)	390
6.5.1	Performance characteristics at constant speed	390
6.5.2	Reactive power flow	396
6.5.3	Effect of variation in shunt capa- citor (C_2)	398
6.5.4	Experimental results	408
6.5.5	Discussion on waveforms	413
6.6	Performance of High-Speed (Flywheel) Machine as LCI-SM with Case E Network (or Case E)	417

6.6.1	Performance characteristics at constant speed	417
6.6.2	Effect of variation of saturable reactor voltage setting for a given value of XC_2	423
6.7	Performance of High-Speed (Fly-wheel) Machine with Case F Network (or case F)	425
6.7.1	Performance characteristics at constant speed	426
6.7.2	Effect of variation in XC_1 on V_L	430
6.7.3	Effect of variation in XC_2 on V_L	
6.7.4	Effect of slope (saturated region) of $V_{SR} - I_{SR}$ characteristics	436
6.8	Conclusion	438

CHAPTER 7 EXPERIMENTAL INVESTIGATIONS ON INDUCTION MACHINE AS SELF EXCITED INDUCTION GENERATOR AND AS LINE COMMUTATED INVERTER FED INDUCTION MOTOR

7.0	INTRODUCTION	442
7.1	Investigation on Self Excited Induction Generator	442

7.1.1	Principle of operation of the self excited induction generator	442
7.1.2	Effect of resistive loading	444
7.1.3	Effect of resistive-inductive loading	445
7.2	Proposed Excitation Scheme	447
7.2.1	Effect of loading	449
7.2.2	Effect of variation in X_{C_2}	449
7.3	Experimental Verification of Proposed Excitation Scheme for Induction Generator	450
7.3.1	Experimental set-up	450
7.4	Performance characteristics of induction generator with proposed excitation scheme	453
7.4.1	No-Load Test	453
7.4.2	Performance characteristics of induction generator with back emf load	456
7.4.3	Effect of variation in saturable reactor voltage setting on performance characteristics (Back emf load)	459
7.5	Experimental Investigation on Line Commutated Inverter Fed Induction Motors	465

7.5.1	Experimental results and discussions	467
7.5.2	Discussions on waveforms of voltage and current	471
7.6	Discussion on Analytical Model	473
7.7	Application of Induction Generator (Self Excited) and Line Commutated Inverted Fed Induction Motor Systems	479
7.8	Conclusion	480
CHAPTER 8	CONCLUSIONS	
8.1	Major Achievements	481
8.1.1	Design of low- and high-speed machines	48
8.1.2	Saturation flux density level and slot size	48
8.1.3	Armature reactance of low and high speed machines	48
8.1.4	Performance of low-speed machine as generator	48
8.1.5	Flat terminal voltage-load current characteristics of low-speed generator	48

8.1.6	Low-speed machine as a line commutated inverter fed motor without armature reaction compensating network	485
8.1.7	Operation of low-speed machine as a variable speed motor with compensating network	485
8.1.8	Stiff torque-speed characteristics	486
8.2	Comparison of Predicted and Experimental Characteristics	486
8.3	High-Speed Machine as Generator	487
8.4	Operation of Self Excited Induction Generator and Induction Motor Fed from a Line Commutated Inverter	487
8.5	Harmonics of Voltage of Synchronous and Induction Machine Systems with Compensating Network	489
8.6	Commutation Overlap	489
8.6.1	Determination of commutation overlap angle with series capacitor	489
8.7	Analytical Results of Hybrid Vehicle System	490
	APPENDICES	493
	REFERENCES	525