

SINGLE PHASE OPERATION OF THREE-PHASE
INDUCTION MOTORS

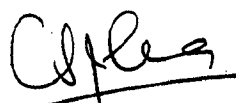
R.S.JHA

Thesis submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy
in Electrical Engineering
of
Indian Institute of Technology, Delhi

1972

CERTIFICATE

Certified that the dissertation entitled "The Single Phase Operation of Polyphase Induction Motors" which is being submitted by Shree Rambhawan Shivnarayan Jha in partial fulfilment for the award of the Degree of Philosophy in Electrical Engineering of the Indian Institute of Technology, Delhi is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.


(C.S.Jha)

Dated: December 30 ,1972.

ACKNOWLEDGEMENT

The investigation was undertaken at the suggestion of Dr.C.S.Jha, Professor of Electrical Engineering at the Indian Institute of Technology, Delhi. The author wishes to acknowledge with thanks the invaluable help and guidance received from him during the investigation and later in the preparation of the thesis.

The author is also thankful to the Director of the Indian Institute of Technology for providing research facilities at the Institute.

Special thanks are due to Messrs. R.P.Sharma, R.N.Singh, Chander Bhan and Meharban Singh Rawat of the Electrical Engineering Laboratory for their sustained help and cordial cooperation during the entire experimental work without which the investigation could never have been possible.

Further the author would like to take this opportunity to express indebtedness to the Ministry of Education, Government of India for the award of scholarship under the Quality Improvement Programme & the Department of Industries and Technical Education, Government of Bihar for sponsoring for higher studies at this Institute.

R.S. Jha

S U M M A R Y

To economise the cost of transmission in low load carrying areas, many State Electricity Boards in India are resorting to the single-conductor ground-return system of transmission for rural electrification. Though the cost of transmission gets considerably reduced, problems arise in the operation of the three-phase motors most commonly used in pump-irrigation systems. Since the number of such pump installations is growing fast, a need is felt to develop a good phase conversion system to allow a proper utilisation of a three phase motor from a single-phase source. The present study was taken up to meet this need.

While the operation of a three-phase motor from a single-phase supply with a capacitor in circuit has been discussed in literature over the years, detailed analytical work has been limited either to the starting of such motors [8] or to its operation with a 2-capacitor system [6]. In the present study, the analysis has been carried out over the entire speed range of the machine with special emphasis on the magnitude of the negative-sequence voltage and the voltage unbalance factor defined as the ratio of the negative sequence voltage to the positive sequence voltage. It has been shown both analytically and experimentally that with a suitable design of the motor and a proper selection of the capacitor size, it is possible to limit the negative-sequence voltage to about 5%. A computer programme has been developed to determine the optimum size of the capacitor at all speeds. The adjustment of the capacitor size is possible through a feedback

ontrol system. However, to keep the cost of the control-gear to a minimum, an investigation has been carried out to see whether a number of discrete capacitor sizes would solve the problem. It has been found that if a three-capacitor system is used, one capacitor corresponding to the starting value, one to the running value, and one to optimise operation at 30% slip, the unbalance during the entire operation is limited to reasonable values. Both computed performance and experimental results show that Haberman's conclusions about the behaviour of the three-phase machine operated from a single-phase supply are extremely conservative if not totally untenable. The feasibility of using a double-cage machine from a single-phase source has been investigated and it has been established that the prejudice against such a usage is indefensible. The double-cage machine the performance of which was both computed from theoretical equations and tested in the laboratory showed better characteristics under single-phase operation than all the single-cage machines examined.

Next part of the investigation relates to the operation of such a machine at two speeds without any major redesign of the windings. The difficulty in operating induction machines at lower speeds is due to the considerable increase in the stator and rotor currents at the lower speed. An earlier work [11] had indicated the possibility of one-third speed operating by utilising 60° or 120° displacement between two windings. A thorough analysis has been carried out to see what would be the best method of getting one-third speed. The conventional zero-sequence connection is examined and compared with other methods. It is found that the best results are obtained when all the three

windings of the machine are utilised, one of them being divided into two parts and reconnected with the other windings to give a 60° displacement between the windings. The currents taken by the windings under this connection were nearly balanced and also the smallest in value when compared to all the other possible configurations examined. Switching arrangements are evolved which necessitate only **six** terminals to be brought out, an economic factor worthy of consideration.

The concluding part of the investigation relates to the dynamic behaviour of a three-phase motor run from a single-phase source through a capacitor. Earlier work by Treschev [13] had indicated large variation between steady-state and dynamic torque in case of normal polyphase operation of an induction motor. An attempt has been made to estimate such variation under single-phase operation. The equations of behaviour obtained are simultaneous differential equations with complex coefficients. A computer program to calculate the behaviour could not be developed because of no known method of solving such equations. Experimental tests on a small laboratory motor however failed to show any appreciable difference between the steady-state and dynamic behaviour of the machine.

The investigation reported in this dissertation has successfully led to:-

- (a) the development of a complete analysis of the behaviour of a single-phase motor operating from a polyphase supply;
- (b) the laying down of useful design criteria for the successful operation of such motor;
- (c) the development of a three-capacitor scheme for reducing the unbalance to a minimum over the entire speed range;
- (d) the development of a new method of operating the motor at $1/3$ -speed with currents in the windings remaining nearly balanced and smaller in value than in all other simple methods of $1/3$ -speed operation; and
- (e) a study of the dynamic behaviour of the single-phase operation of polyphase motor.

CONTENTS

<u>CHAPTER</u>		<u>Page</u>
	Summary	1
I	Introduction	5
II	The Operation of a Three-phase Induction Motor connected to a Single-phase Supply System	
	2.1 General	12
	2.2 Analysis of Performance	13
	2.2.1 General Equations	13
	2.2.2 Phase Currents	16
	2.2.3 The Developed Torque	17
	2.2.4 Voltage across the converter	19
	2.2.5 Voltage Unbalance	20
	2.3 Optimisation of Converter Size	20
	2.3.1 Converter Size for minimum unbalance	21
	2.3.2 Converter size for minimum V_2	22
	2.3.3 Converter Size for $V_2=0$	23
	2.4 Computation of Characteristics	24
	2.4.1 Selection of Machines	24
	2.4.2 Calculation of Machine Parameters	25
	2.4.3 Computed Results	29
	2.5 Discussion of Computed Results	42
	2.5.1 Unbalance Factor	42
	2.5.2 Net Torque Developed	42
	2.5.3 Voltage across the converter	45
	2.5.4 The loss coefficient	45
	2.6 The Two-capacitor System	47
	2.7 The Three-capacitor System	50
	2.8 Experimental Results	54
	2.8.1 Test Machines	54
	2.8.2 Discussion of experimental results	55
	2.8.3 Use of discrete capacitors	59
	2.8.4 Heat run of Machine No.4	60
	2.9 Design Consideration for Satisfactory Operation of Polyphase machines from Single-phase System	61
	2.9.1 Choice of Converter size	61
	2.9.2 The Role of machine phase angle α_1	64
	2.9.3 Machines with deep-bar rotor or a double-cage rotor	65
	2.9.4 Tests on a double-cage rotor	73
	2.10 Conclusions	73

III	Two Speed (3:1) Operation of A 3-phase Induction Machine from a Single-phase Supply	
3.1	General	78
3.2	Methods of Speed Control	78
3.3	Third harmonic torques in the single-phase operation of polyphase machines	81
3.3.1	General	81
3.3.2	Analysis of the machine with six possible alternative connections of the stator winding.	82
3.3.3	Comparison of the characteristics obtained for the six different stator winding arrangements	86
3.3.4	Analysis of the machine performance when an external admittance has been connected in series with one of the windings	89
3.3.5	Comparison of performance under different winding connections with external admittance in circuit	93
3.4	Split-winding arrangement of the three-phase windings of the machine to give effectively a two-winding connection with 60° or 120° displacement.	94
3.5	Analysis of the behaviour of the machine having the split-winding arrangement for utilising all the winding space	99
3.5.1	The S-1 connection	99
3.5.2	The S-2 connection	100
3.5.3	The D-1' connection	102
3.5.4	The D-2 connection	104
3.5.5	Verification of the solutions of the split-phase analysis through comparison of limiting conditions with other methods	105
3.6	Computation of Behaviour of the machine with split-phase arrangement	107
3.6.1	Specifications and parameters of the machine selected for comparison	107
3.6.2	Computer results	108
3.6.3	Discussion of the computed results	129

(iii)

3.7	The Two-speed Operation of the Machine	132
3.7.1	Choice of winding configurations	132
3.7.2	The switching arrangement	133
3.7.3	The capacitor value to be used at lower speed of both Figs. 3.13 and 3.14	135
3.8	Experimental Results	136
3.8.1	The Test machine	136
3.8.2	The Performance tests	136
3.8.3	Discussion of the experimental results	137
3.8.4	Test run on two-speeds	138
3.9	Design Considerations	139
3.10	Conclusions	140
IV	The Dynamic Behaviour of Three-phase Induction Motors Operated from Single-phase Supply.	
4.1	General Considerations	141
4.2	Assumptions	144
4.3	Equations of Performance	145
4.4	Conclusions	150
V	Main Conclusions and Suggestions for Future Work	
5.1	Main Conclusions	151
5.2	Suggestions for future work	154
5.2.1	Use of deep-bar and double-cage rotors	154
5.2.2	Design of suitable stator windings for two-speed operation	154
5.2.3	Dynamic behaviour of machines	155
	BIBLIOGRAPHY	156
	APPENDIX	161