Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
87-20

Study of the Generator/Motor Operation of Induction Machines in a High Frequency Link Space Power System

T. A. Lipo and P. K. Sood
Department of Electrical and Computer Engineering
University of Wisconsin-Madison
1415 Johnson Drive
Madison, WI 53706-1691

WEMPEC

Department of Electrical and Computer Engineering
1415 Johnson Drive
Madison, Wisconsin 53706
July 1987
Study of the Generator/Motor Operation
of Induction Machines
in a High Frequency Link Space Power System

Contract No. NAG3-631
Final Report

by

University of Wisconsin
Department of Electrical and Computer Engineering
1415 Johnson Drive
Madison, WI 53706

Thomas A. Lipo
Principal Investigator
and
Predeep K. Sood
Project Engineer

Prepared for

NASA Lewis Research Center
Cleveland, OH 44135

Irving G. Hansen
NASA Project Manager

September, 1986
Abstract

Static power conversion systems have traditionally utilized dc current or voltage source links for converting power from one ac or dc form to another since it readily achieves the temporary energy storage required to decouple the input from the output. Such links, however, result in bulky dc capacitors and/or inductors and lead to relatively high losses in the converters due to stresses on the semiconductor switches. This report examines the feasibility of utilizing a high frequency sinusoidal voltage link to accomplish the energy storage and decoupling function. In particular, a new type of resonant six pulse bridge interface converter is proposed which utilizes zero voltage switching principles to minimize switching losses and uses a novel, easy to implement technique for pulse density modulation to control the amplitude, frequency and the waveshape of the synthesized low frequency voltage or current. Adaptation of the proposed topology for power conversion to single-phase ac and dc voltage or current outputs is shown to be straightforward. The feasibility of the proposed power circuit and control technique for both active and passive loads are verified by means of simulation and experiment.
# Contents

1 Introduction .................................................. 1

  1.1 Objective of the Research ................................. 2

  1.2 Applications of High Frequency Link Converters .......... 3

  1.2.1 Orbiting Space Station ................................. 3

  1.2.2 Aircraft Secondary Power System ....................... 5

  1.3 Brief Summary of This Report ............................. 7

  1.4 References ................................................ 8

2 Induction Machine - High Frequency Link Interface Considerations 10

  2.1 Terminal Characteristics of Induction Machines ............ 10

  2.1.1 Reactive Power Requirements ........................... 10

  2.1.2 Operation with Sinusoidal Supply Having Fixed Frequency and Amplitude ......................... 11

  2.1.3 Sinusoidal Supply Having Variable Frequency and Amplitude .................................. 11

  2.1.4 Operation from a Converter Supply ....................... 15
2.2 Desirable Characteristics of the Interface Converter .............. 15

2.3 Interface Converter Topologies ......................................... 17

2.3.1 Intermediate DC Link Converter, Fig. 2.5(a) ...................... 17

2.3.2 Resonant Converter with an Exciter, (Fig. 2.5(b)) .............. 21

2.3.3 Resonant Converter Without an Exciter, Fig. 2.5(c) .......... 21

2.3.4 Phase Controlled Cycloconverter, Fig. 2.5(d) ................... 21

2.3.5 Pulse Density Modulated Converter, Fig. 2.5(e) .............. 22

2.4 Topologies Studied in This Report ..................................... 22

3 Resonant Circuit Based Interface Converter .......................... 23

3.1 The Parallel Output Series Resonant (POSR) Circuit ............. 23

3.1.1 Circuit Operation of POSR Converter ............................. 25

3.1.2 Converter Losses .................................................. 27

3.1.3 Effect of Loading .................................................. 30

3.1.4 Control of High Frequency Voltage ............................... 30

3.2 Circuit Adaptation for AC Inputs ...................................... 33

3.2.1 Adverse Affects of Source Impedance ............................ 33

3.2.2 Decoupling Effect of an Input Capacitor ........................ 36

3.3 Circuit Topology and Operation for Three-Phase Input .......... 36
3.3.1 120° Phase Shifted Gating. ........................................ 40
3.3.2 Synchronized Gating. ............................................. 42
3.4 Feasibility of POSR Converter as an Interface Converter ......... 44
3.5 References .................................................................. 44

4 Pulse Density Modulated Interface Converter .......................... 46

4.1 Modulation Considerations ............................................ 46
  4.1.1 Limitations of Phase Angle Control Cycloconverters. .......... 46
  4.1.2 Advantages of Zero Voltage Switching ......................... 47
  4.1.3 Technique of Pulse Density Modulation (PDM) ............... 47
  4.1.4 Fundamental Relationships in Pulse Density Modulation. .... 50

4.2 PDM Synthesis of Three-Phase AC .................................. 52
  4.2.1 Converter Power Circuit. ......................................... 52
  4.2.2 Converter Power Switches. ..................................... 52
  4.2.3 PDM Synthesis of a Balanced Set of Three-Phase Voltages. 57

4.3 Interfacing of Induction Machines Using PDM Bridge Converter .. 60

4.4 Characteristics of PDM Converter as an Interface Converter .... 65

4.5 References ............................................................... 65
5 Experimental System

5.1 Description of the Laboratory System ........................................ 67
  5.1.1 Excitation Inverter......................................................... 69
  5.1.2 Three-Phase PDM Converter........................................... 74
  5.1.3 PDM Converter Control.................................................. 74
5.2 Test Results and Discussions ................................................ 78
  5.2.1 Excitation Inverter......................................................... 78
  5.2.2 Tank Filter...................................................................... 83
5.3 PDM Converter .................................................................... 86
  5.3.1 Pulse Density Modulation............................................... 86
  5.3.2 Passive R-L load.............................................................. 91
  5.3.3 Induction Machine Load.................................................. 97

6 System Operation .................................................................. 104

6.1 PDM Synthesis of Single Phase AC and DC .......................... 104
  6.1.1 PDM Synthesis of DC or Single-Phase AC Voltages.......... 104
  6.1.2 PDM Synthesis of Single-Phase Currents...................... 110
6.2 Proposed System Configuration ............................................. 110
  6.2.1 Description of the System Configuration....................... 110
6.2.2 System Operation and Control ........................................ 113
6.2.3 Effects of PDM Converter Operation on the Link .............. 116
6.2.4 Link Filter .............................................................. 121

6.3 Effect of the Link Voltage "Ripple" ................................. 121

6.4 System Start Up ......................................................... 122

6.5 Characteristics of the Proposed System .............................. 122

6.6 References .............................................................. 124

7 Conclusions and Suggestions for Further Work ..................... 125

7.1 Conclusions .............................................................. 125

7.2 Suggestions for Further Work ........................................ 127

7.2.1 Active Energy Storage in the Link ............................... 127

7.2.2 Alternate PDM Circuit Topologies ................................. 127

7.2.3 Study of Switching Strategies ..................................... 128

7.2.4 Alternate Filter Configurations .................................... 128

7.2.5 Application to Dedicated Power Conversion Systems .......... 128

7.2.6 Further Experimental Work ........................................ 129

8 Selected Bibliography .................................................... 130
A An Induction Machine Model with Saturable Main Flux 135
  A.1 Development of the Model ............................. 136
  A.2 Verification of the model. .............................. 143
  A.3 References ............................................. 143

B Modelling the Parallel Output Series Resonant (POSR) Converter 149
  B.1 Development of the Model ............................. 149
    B.1.1 Power Circuit. .................................... 149
    B.1.2 Modeling of the bi-directional switch. .......... 151
  B.2 Circuit Equations. ................................. 153
    B.2.1 Gating Signals. ................................. 154
  B.3 Verification of the Model .............................. 157

C Modelling of Pulse Density Modulated (PDM) Converters 162
  C.1 Development of the Three-Phase Bridge Model .... 162
    C.1.1 Power Circuit. .................................... 162
    C.1.2 Circuit Equations ................................ 167
    C.1.3 PDM Logic. ....................................... 171
  C.2 Verification of the Model .............................. 172
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.3 Modeling Single-Phase PDM Converters</td>
<td>172</td>
</tr>
<tr>
<td>C.4 Voltage Synthesis</td>
<td>176</td>
</tr>
<tr>
<td>C.5 Current Synthesis</td>
<td>176</td>
</tr>
</tbody>
</table>