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Participating Societies

PROCEEDINGS OF THE 24th INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

VOLUME 2 Advanced Rotating Machines
Thermal Electrochemical Systems
Thermoelectrics
RTG's
Photovoltaics
Space Solar Dynamic Systems
Magnetohydrodynamic Power Generation
Burst and Pulse Power
Space Dynamic Conversion
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Editor:
William D. Jackson
Associate Editor:
Dorothy A. Hull

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS
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PREFACE

The scope of the Intersociety Energy Conversion Engineering Conference (IECEC) series has grown from a straightforward treatment of energy conversion engineering to a broad involvement in all aspects of energy systems, including primary resource processing, utilization and environmental issues in addition to conversion and storage. The other notable trend has been toward increased international participation and, as the papers in this volume attest, IECEC-89 can truly claim to be an international forum on energy engineering with a significant proportion of the papers being presented being from beyond the confines of the United States. It is a particular pleasure to include, for the first time, a sizeable contribution from the USSR.

These developments are indeed appropriate for energy conversion engineering has to be undertaken within the broader context of energy systems and energy issues which are not constrained by national boundaries. The increasing and proper concern for the impact of energy systems not only locally but also globally is particularly reflected in the nearly 500 papers appearing in a Proceedings which has now grown to six volumes. In these, the reader will find a comprehensive coverage of recent work on energy systems and technologies relevant to the expected conditions of the 1990's and beyond. The international character of IECEC-89 shows not just through participation from many countries but the large measure of common ground evident in the contributions made by the many national and international organizations involved in the energy engineering field.

The organization of this large amount of interrelated material poses considerable challenges which have been met in the first instance by dividing the Conference and, by extension, the Proceedings, into a number of major topical areas. From a narrow applications viewpoint, it is tempting to view aerospace and terrestrial energy system issues separately since they generally involve meeting different criteria. This has not been done in the present Conference in large measure because an IECEC objective is to find and emphasize points of commonality. Accordingly, a blend of interests will be found throughout, as for example, in Volume 2 devoted to energy conversion technologies where space and terrestrial photovoltaics are grouped together.

To facilitate use of the volumes, the Table of Contents is repeated in each Volume and an author Index appears in Volume 6. In addition, the now well-established feature of IECEC, the SAE cumulative index for the past four years is also included in Volume 6. This may be used to locate recent related work reported at the IECEC and, in due course, it will be updated to include the current Conference.

The task of preparing these Proceedings has only been possible through the unstinting efforts of the Program Committee, Session Organizers and the IECEC-89 staff whose many contributions are gratefully acknowledged by the Editors. In fairness to other technologies in which the Institute of Electrical and Electronics Engineers is prominently involved, the critical role of computers, FAX machines and other aspects of modern communications technology in permitting the assembly of this body of material also deserves recognition.

William D. Jackson, *Editor*
Dorothy A. Hull, *Associate Editor*

24th Intersociety Energy Conversion Engineering Conference

Gateway Marriott Hotel, Arlington, VA

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Christine H. Auldridge	Tel: (202) 686-9141
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VOLUME II
Conversion Technologies and Space Nuclear Reactor Systems

CONVERSION TECHNOLOGIES I
ADVANCED ROTATING MACHINES

SPACE ENERGY CONVERSION TECHNOLOGIES V
STATIC CONVERSION I: THERMOELECTROCHEMICAL SYSTEMS

SPACE ENERGY CONVERSION TECHNOLOGIES VIII
STATIC CONVERSION II: THERMOELECTRICS

SPACE ENERGY CONVERSION TECHNOLOGIES I
ADVANCED SPACE SOLAR CELLS

SPACE ENERGY CONVERSION TECHNOLOGIES II
SPACE PHOTOVOLTAIC TECHNOLOGY:
CELL AND ARRAY COMPONENT PERFORMANCE

SPACE ENERGY CONVERSION TECHNOLOGIES III
ADVANCED SPACE SOLAR ARRAYS: PERFORMANCE AND REQUIREMENTS

SPACE ENERGY CONVERSION TECHNOLOGIES VI ADVANCED SOLAR DYNAMIC SPACE POWER-MISSIONS, TECHNOLOGY AND APPLICATIONS

SPACE ENERGY CONVERSION TECHNOLOGIES IX

SPACE ENERGY CONVERSION TECHNOLOGIES XI SPACE STATION SOLAR DYNAMIC POWER SYSTEMS—COMPONENT TECHNOLOGY

SPACE ENERGY CONVERSION TECHNOLOGIES XIII
ADVANCED SOLAR DYNAMIC SPACE POWER SYSTEMS—RECEIVERS/THERMAL STORAGE

CONVERSION TECHNOLOGIES II
MHD I—RETROFIT AND POWER TRAIN STUDIES

CONVERSION TECHNOLOGIES III
MHD II—GENERATORS, HEAT RECOVERY AND SEED REPROCESSING

CONVERSION TECHNOLOGIES IV
MHD III ALTERNATIVE CONCEPTS

BURST AND PULSE POWER

SPACE ENERGY CONVERSION TECHNOLOGIES IV
DYNAMIC CONVERSION

BURST SPACE POWER

CONVERSION TECHNOLOGIES V
THERMIONICS I: PHYSICS AND ADVANCED TECHNOLOGIES

CONVERSION TECHNOLOGIES V
THERMIONICS—COMPONENTS AND METHODS (USSR)

CONVERSION TECHNOLOGIES VII
THERMIONICS PERFORMANCE TESTING

SPACE NUCLEAR REACTOR SYSTEMS I
SPACE REACTOR APPLICATIONS

SPACE NUCLEAR REACTOR SYSTEMS II
SP100 TECHNOLOGY

SPACE NUCLEAR REACTOR SYSTEMS III
TECHNOLOGY I

SPACE NUCLEAR REACTOR SYSTEMS IV
TECHNOLOGY II

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MODES OF OPERATION OF THE SLIP RING INDUCTION MACHINE IN WIND ENERGY CONVERSION SYSTEMS

M.T.El Hagry | A.A.Mohamed | M.N.Iskander

Elect. Research Inst. National Research Centre Cairo,Egypt

Faculty of Eng.& Tech. Menoufia University Egypt

Elect. Research Inst. National Research Centre Cairo,Egypt

ABSTRACT

The aim of this paper is to thoroughly investigate two modes of operation of the slip ring induction machine, namely the Double Output Induction Generator (DOIG) and the Double Excited Induction Generator when used in Wind Energy Conversion Systems(WECS). A comparison between the output power, power factor, efficiency, system displacement angle, and firing angle is done. A scheme of operation combining both modes for optimum operation is proposed.

INTRODUCTION

In this research the steady state performance of the slip ring induction machine running at super synchronous speed in wind energy conversion systems (WECS) is investigated. Two modes of operation, namely, the double output induction generator(DOIG) and the double excited induction generator (DEIG) have been evaluated for comparison purposes and for the deduction of the optimum implementation of the slip ring induction machine as a generator in WECS. These modes of operation are characterized by the variable speed constant frequency (VSCF) property for wind energy conversion, which is superior to the constant speed, constant frequency (CSCF) systems from the point of view of the collection of electric energy from the available wind power [1,2]

In both modes, namely, the DOIG and the DEIG, the stator is connected to the a.c. grid, while the rotor is connected to the grid via two controllable bridges (BRG1 and BRG2) seperated by a d.c. link. BRG1 is connected to the rotor terminals and BRG2 is connected to the grid as shown in Fig.1. When the first mode of operation, DOIG, is conducted, BRG1 is operated as a full wave rectifier at zero firing angle, while BRG2 is operated as an inverter at the grid frequency varying its firing angle in an optimal manner. When the second mode of operation (DEIG) is conducted, bridge BRG1 is operated as an inverter at slip frequency, while BRG2 is operated as a controllable rectifier.

A central control unit is designed to generate the timing pulses for the two bridges according to the mode of operation required at each speed.

For the purpose of comparison, the induction machine is operated in the two proposed modes under the same operating conditions, namely:

1. constant stator voltage
2. constant stator current, and same range of rotor speeds

The steady state chracteristics deduced includes the active power generated, the reactive power consumed, the system efficiency, and the mode of variation of the firing angles. From these characteristics a control strategy is proposed to optimize the performance of the generator according to the system requirements.

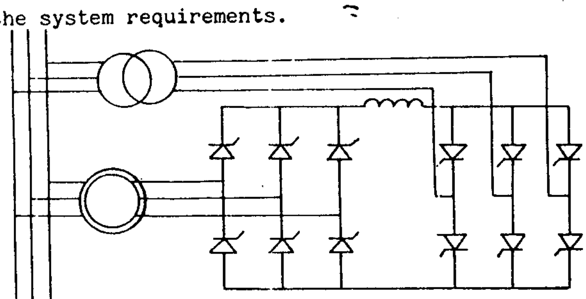

Fig. 1.

The Double Output Induction Generator (DOIG)

In this mode, BRG1 is operated as a full wave rectifier at zero firing angle, while BRG2 is operated as an inverter with variable firing angle. The inverter firing angle α_i is varied so as to keep the stator current constant and equal to its rated value to allow more than the induction machine rated power to be delivered to the supply without overheating the machine. Varying α_i is represented by an additional variable resistance R_x inserted in the rotor circuit [3]. Thus the equivalent circuit is as shown in Fig.(2). The equivalent circuit impedance is

$$Z_{eq} = R_{eq} + j\,X_{eq} \tag{1}$$

$$= |V_s| \;/\; |I_s| \tag{2}$$

Since the stator voltage and current are constant, R_x could be obtained at each slip by solving eq. (2).

To derive the relation between R_x and α_i assuming lossless rectifier and inverter, the following relations hold:

The average output rectifier voltage is

$$V_{rec} = 3\sqrt{6}\;\; V_v \,/\, \pi \tag{3}$$

where

$$V_v = I_r\, R_x / S. \tag{4}$$

$$I_r = V_{ag} / \sqrt{R_2^2 + X_r^2} \tag{5}$$

$$R_2 = (R_r + R_x)\,/S \tag{6}$$

The average input voltage of the inverter is

$$V_{inv} = 3\sqrt{6}\; V_s \cos\alpha_i \,/\, \pi \tag{7}$$

Neglecting losses in the d.c. link,

$$V_{rec} = -\,V_{inv} \tag{8}$$

From equations 4 to 8

$$\alpha_i = \cos^{-1}\,(I_r\, R_x / S\, V_s) \tag{9}$$

Fig.(3) shows variation of R_x and α_i with S

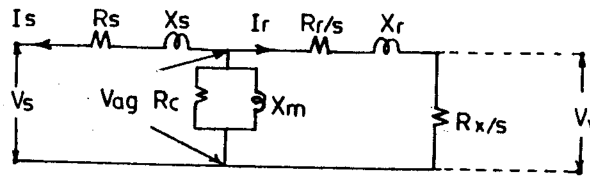

Fig.2. Equivalent circuit of DOIG

The inverter active and reactive powers are

$$P_{inv} = 3V_s\, I_r \cos\alpha_i \tag{10}$$

$$Q_{inv} = 3V_s\, I_r \sin\alpha_i \tag{11}$$

The stator active and reactive powers are

$$P_s = 3V_s\, I_s \cos\theta_s \tag{12}$$

$$Q_s = 3V_s\, I_s \sin\theta_s \tag{13}$$

Thus the total active and reactive powers of the DOIG are

$$P_t = P_{inv} + P_s \tag{14}$$

$$Q_t = Q_{inv} + Q_s \tag{15}$$

A parameter "ε", defined as "system displacement coefficient" is calculated and given by:

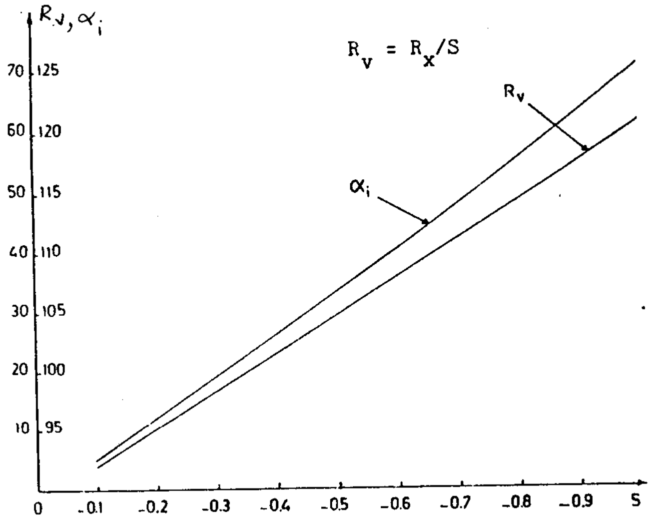

Fig.3. Variation of R_v and α_i with slip

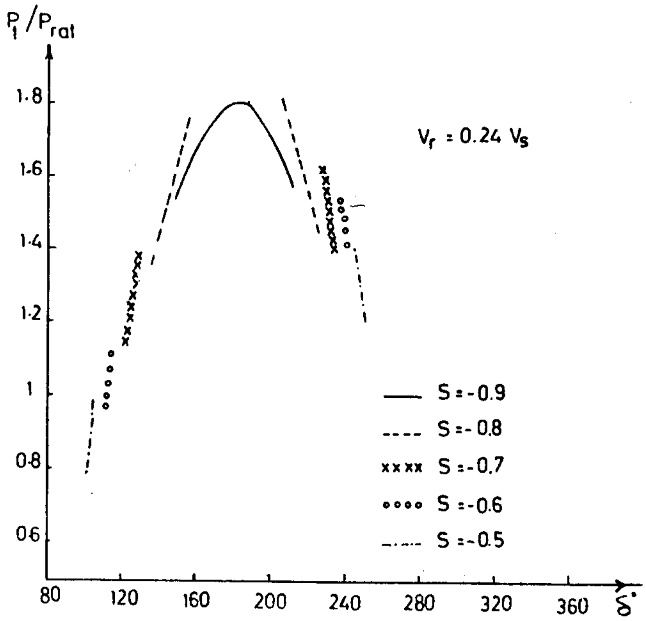

Fig.4. Variation of P_t/P_{rat} with δ at different slips

$$\epsilon = P_t / Q_t \tag{16}$$

The mechanical power input is

$$P_m = 3(1-S)\ I_r^2\ R_2 \tag{17}$$

Neglecting friction and windage losses, the system efficiency is given by:

$$\eta = P_t / P_m \tag{18}$$

The Double Excited Induction Generator (DEIG)

In the DEIG mode of operation BRG1 is operated as an inverter with firing angle α_i, and BRG2 is operated as rectifier with firing angle α_r. Thus a voltage at slip frequency is injected to the rotor circuit, whose magnitude V_r and phase angle δ are changed by varying α_r and α_i respectively. To get value of δ which gives maximum value of P_t/P_{rat}, the terminal voltage machine equations in the d-q axes rotating at the synchronous speed W_s are solved in the steady state for different values of slip S.

These equations are given by [4] :

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s+L_sp & -W_sL_s & M_op & -M_oW_s \\ W_sL_s & R_s+L_{sp} & W_sM_o & M_op \\ M_op & -SW_sM_o & R_r+L_rp & -SW_sL_r \\ SW_sM_o & M_op & SW_sL_r & R_r+L_rp \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} \tag{19}$$

where $V_{ds} = V_{sm}$, $V_{qs} = 0$

$V_{dr} = V_{rm} \cos \delta$

$V_{qr} = -V_{rm} \sin \delta$

The total active and reactive power are

$$P_t = V_{ds}\ I_{ds} + V_{dr}\ I_{dr} + V_{qs}\ I_{qs} + V_{qr}\ I_{qr} \tag{20}$$

$$Q_t = V_{ds}\ I_{qs} + V_{qs}\ I_{ds} + V_{dr}\ I_{qr} + V_{qr}\ I_{dr} \tag{21}$$

The generated active power as a ratio of the machine rated power is plotted as function of δ at different slips and constant V_r in Fig.4, where

$$V_r = (V_{dr}^{\ 2} + V_{qr}^{\ 2})^{1/2}$$

Fig.(4) shows the plotting of P_t/P_{rat} against δ for different values of S. It is noticed that for S = -0.9 the ratio P ($P = P_t/P_{rat}$) reaches 1.8, i.e. the generated active power is higher than the