

```

\documentclass[12pt, chapup]{bitirme}
\input rotate.tex
\input psfig.sty

\usepackage{latexsym} % required for some math symbols
\usepackage{amsmath}
\usepackage{rotating}

% Bu satirdan ustteki satirlari degistirmemenizde fayda vardir.
%
% *****

% Bitirme odevinizin basligini buraya yaziniz \title{ }
%
\title{RÜZGAR ENERJİ SANTRALLERİNDE KULLANILAN GENERATÖR
TİPLERİ}

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% Oğrenci numaraniz
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\stnumber{485354}

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% Ozet kısmi buraya yaziliyor
%
\abstract[short]
{
Most wind turbines in service today employ induction generators
together with a step-up mechanical gear so that the operational speed
is close to the synchronous speed of two or four-pole generators.
Because of the torque-speed characteristic of induction generators,
the range of speed change is rather small; therefore, the operational
speed can be considered to be nearly constant. Mechanical gears are
subject to wear and tear, reduce reliability of the drive train and
add to its weight. The maximum power that can be extracted from wind
varies with its speed. Therefore, a direct-drive system, where a
wind turbine is directly coupled to the generator shaft, is
desirable along with a variable-speed operation.

The variable-speed, direct-drive train described in this thesis
consists of a low-speed, permanent-magnet generator (60 to 120rpm),
a resonant rectifier and a pulse-width-modulated inverter. It
supplies 30kVA/20kW apparent/real power to the utility system at
leading and unity power factors for a given DC link voltage. The
amplitude and phase (leading, unity) of the AC current delivered to

```

RÜZGAR ENERJİ SANTRALLERİNDE
KULLANILAN GENERATÖR TİPLERİ

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485354

BİTİRME ÖDEVİ

Haziran 2000

Danışman: Y. Doç. Dr. DENİZ YILDIRIM

İSTANBUL TEKNİK ÜNİVERSİTESİ
ELEKTRİK ELEKTRONİK FAKÜLTESİ

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the utility system are controllable and the voltage/current wave forms at the point of common coupling satisfy standard IEEE-519. The overall efficiency of the drive train is about 83% (excluding the generator), whereby the rectifier has an efficiency of 86% and the inverter efficiency is around 95%.

Using two different approaches (computer-aided and three-voltmeter methods), the losses of inductors are measured for the frequency range of 0 to 6kHz. Measurement errors of both methods are less than 10% when measuring a few watts. The AC resistance increase of a Litz-wire inductor without a core is smallest among all of the inductors being tested. Stranding of individual (uninsulated) wires to obtain a flexible cable results in more losses than using a solid cable having the same cross-sectional area as that of a stranded cable.

Nonsinusoidal voltages and currents in a power system can produce an additional power, called distortion power, generated from the cross products of voltage and current harmonics of different frequencies. This additional power increases system losses that cannot be easily compensated. Existing definitions of distortion power are not quite correct either from a numerical or a physical point of view because they involve voltage and current harmonics of the same frequency; therefore, a correct formulation is given which agrees well with experimental results.

When a transformer is operating under nonsinusoidal voltages and currents, its apparent power output must be reduced (derating) in order not to exceed the rated temperature. Comparison of measured derating values with ones obtained from K -factor and F_{HL} -factor approaches reveals that the K -factor approach yields somewhat greater derating values than the F_{HL} -factor approach. The losses of conductive materials in the presence of magnetic fluxes are also investigated and it has been found that the maximum losses in these components occur at a specific (material-dependent) frequency. The losses are proportional to the power of 0.8 below this frequency and are inversely proportional to the power of 0.9 above this frequency.

```
%
%Tesekkur etmek istediginiz kisiler
%
\acknowledgements{
Bu tezin hazırlanmasında benden yardımlarını esirgemeyen değerli
arkadaşlarıma ve aileme teşekkürü bir borç bilirim.
}

% Sembol listesini tablo şeklinde buraya yazabilirsiniz.
% Eger böyle bir liste kullanmak istemiyorsanız bu kısmı
% silebilirsiniz
%
\symbollist{
\begin{tabular}{l l}
 $\mu$  & permeability
\end{tabular}
}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Bitirme Odeviniz bu noltadan itibaren basliyor, her yeni bir
% bolumu \chapter{ } komutuyla basliyabilirsiniz.
%
\begin{document}

\chapter{INTRODUCTION}
```

ÖNSÖZ

Bu tezin hazırlanmasında benden yardımlarını esirgemeyen değerli arkadaşlarıma ve aileme teşekkürü bir borç bilirim.

During the past ten years of research, design and construction of a 30 kVA variable-speed (\$60\$ to \$120 rpm\$) direct-drive wind power plant has been conducted in the Department of Electrical and Computer Engineering of the University of Colorado at Boulder. Most support for this project \cite{yildirim} was provided by the National Renewable Energy Laboratory (NREL) in Golden. The primary work for design and construction of the low-speed permanent magnet generator is described in \cite{batan}. This generator has been extensively tested \cite{mohan} and mounted on a tower at the National Wind Technology Center (NWTC) of NREL. The \$30 kVA\$ three phase PWM (pulse-width-modulated) inverter has been tested on the bench and reported in \cite{yildirim} for output powers of \$20 kW\$ at about unity-power factor, without employing a transformer between the inverter and the power system of Public Service Company of Colorado, and without final mounting of the components within a steel cabinet. The zero-current-switch resonant rectifier has been assembled and tested \cite{yildirim} on the bench up to \$3.2 kW\$ at low input and output voltages without control of the output voltage, and the components did not work properly within the environment of a steel cabinet.

Preliminary results of the above work have been reported in \cite{ti}, and two invention disclosures were submitted to the Office of Intellectual Resources and Technology Transfer of the University of Colorado at Boulder \cite{iec55}.

The goal of this dissertation was to resume the work on the design and testing of the individual components of this project - the resonant rectifier, the PWM inverter including the current control for real/reactive/apparent powers - and to make all components work together so that, for a variable turbine speed varying from 60 to 120 rpm, a variable power at constant nominal frequency (e.g., 60 Hz) and at constant nominal voltage (e.g., 240 \$V_{L-L}\$) is supplied to the utility system, whereby the current wave shapes including the displacement factor and current amplitude are controllable.

The work of this dissertation encompasses the following topics:

- \begin{enumerate}
- %
 - \item 20 kW Three-Phase, Zero-Current-Switch (ZCS) Resonant Rectifier.
- %
 - \begin{itemize}
 - %
 - \item Redesign of the input filter for higher voltage (\$600V\$) and current (\$40A\$) stresses. A damping network is also added to the input filter.
 - %
 - \item Series connection of input bridge diodes to accommodate higher voltage (2000V) stresses.
 - %
 - \item Redesign of tank diodes and transistor (IGBT, insulated-gate-bipolar transistor) for higher voltage (\$1400V\$) and current (\$200A\$) stresses.
 - %
 - \item Design of the control circuit providing constant DC output voltage (e.g., 360 V) at variable AC input voltage (e.g., 300 \$V_{L-L}\$ to 600 \$V_{L-L}\$)

İÇİNDEKİLER

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```

%
\item Mounting of rectifier components within a steel cabinet, and
solution of EMI (electromagnetic interference) problems.
%
\item Debugging of the rectifier to deliver, at rated inputs, the
rated output quantities.
\end{itemize}
%
\item 30 kVA Three-Phase Current-Controlled PWM Inverter.
%
\begin{itemize}
%
\item Employment of a three-phase transformer between inverter
and power system.
%
\item Debugging of the phase-lock-loop and gating circuits and to
improve their operating stability.
%
\item Addition of a harmonic tuned filter at the point of common
coupling (PCC) to reduce the high frequency harmonic current flowing
into
the power system and to obtain a sinusoidal voltage waveform at the
output of inverter before connecting it to the power system.
%
\item Before connecting to the utility system, the required AC
sinusoidal
output voltage ( $260V_{L-L}$  AC) for a given DC input
voltage (340V DC) can be obtained by operating the PWM inverter with
a
modulation index greater than 1 ( $m > 1$ ) -- independent of the
operating point of the inverter. This operating mode is novel: it
improves the sinusoidal wave shape of the inverter output voltage and
current, reduces switching losses, and reduces the input DC voltage
required when compared to PWM with  $m < 1$ .
%
\item Introduction of a phase-shifting input transformer, to make
the displacement power factor of the inverter adjustable.
%
\item Mounting the inverter components within a steel cabinet
and to remove parasitic EMI problems.
%
\item Establishing control surfaces for apparent power  $S$  and real
power  $P$  as a function of the reference-current signal
 $V_{I_{ref}}$  varying between 0.9V and 7V.
%
\item The real and reactive power flow generated by the PWM inverter
and
fed into the utility system is investigated using fundamental and
harmonic phasor analyses.
%
\end{itemize}
%
\item Joint operation of the ZCS rectifier and the PWM inverter --
mounted in steel cabinets --
delivering rated power to the utility system.
%
\item Conceptual design of a Transversal Flux Machine
(either motor or generator), providing high torques (5 kNm to 2.5
kNm) at low speeds (60 rpm to 120 rpm) based on alternating magnetic
field theory. The work of \cite{ti} has been extended and two
invention disclosures have been submitted \cite{iec55}.
%
\item In a circuit where the load is nonlinear or the source has
nonsinusoidal quantities, the apparent power is not simply
 $S = \sqrt{P^2 + Q^2}$ : another type of power called distortion power
(D) is generated by the cross products of voltage and current

```

SEMBOL LİSTESİ

μ permeability

ŞEKİL LİSTESİ

Şekiller

- | | | |
|-----|--|---|
| 1.1 | Power versus wind speed at two different rotor speeds [6]. | 4 |
| 1.2 | 30 kVA variable-speed, direct-drive wind power plant. | 4 |

harmonics of different frequencies. For nonsinusoidal voltages and currents the apparent power is defined as $S = \sqrt{P^2 + Q^2 + D^2}$. This additional power D increases the load current (apparent power S gets larger) and causes additional losses. Past definitions of the distortion power are reviewed and most are found not to be correct either from a numerical or physical point of view. A proper formulation is derived for the computation of D from the individual voltage and current harmonics not containing voltages and currents of the same frequency. Experiments are performed to measure the distortion power for a variety of load conditions, i.e., for different THD_i and THD_v values.

`%`
`\item` Measurement of losses of inductors employed in different parts of the drive system, using two different approaches. Two methods for measuring losses of inductors at frequencies from 0 to 6kHz are discussed; the first involves the use of sampled inductor voltage and current wave forms through an A/D converter and a computer. The second, called three-voltmeter method, consists of recording the rms values of three sinusoidal voltages. Error analyses of the two approaches are presented.

`\item` Measurement of the derating of single-phase transformers operating at nonsinusoidal voltage and current wave forms, and comparison of the measured derating values with those obtained from K-factor and harmonic-loss factor (F_{HL}) approaches.
`\end{enumerate}`
`%`

In the following it is assumed that the reader is familiar with the primary references of this work \cite{yildirim} to \cite{batan} and an effort will be made to complement and if necessary correct the statements and ideas of these references - thus repetition will be avoided.

Many of today's wind turbines employ standard, off-the-shelf induction generators, along with a step-up mechanical gear operating at nearly constant speeds. Mechanical gears are subjected to wear and tear, are expensive, reduce reliability \cite{batan}, reduce efficiency of the drive train and add to its weight. Therefore, in wind power generating plants, direct-drive trains without any mechanical gears are desirable. Figure \ref{jvarwind} illustrates the power curve of a wind turbine at

`%`
`\begin{figure}[htb]`
`\caption{Power versus wind speed at two different rotor speeds`
`\cite{yildirim}.}`
`\label{jvarwind}`
`\end{figure}`
`%`

two different wind speeds \cite{yildirim}, where the output power of the wind turbine for a given wind speed peaks to a maximum value. Therefore, by allowing the rotor speed to vary with the wind speed, wind turbines can extract the maximum power available at different wind speeds \cite{batan}.

Figure \ref{jsimpdr} shows the schematic diagram of a variable-speed,

`%`
`\begin{figure}[htb]`
`\caption{30 kVA variable-speed, direct-drive wind power plant.}`
`\label{jsimpdr}`
`\end{figure}`
`%`

direct-drive wind power plant. The permanent magnet (PM) generator operating at low speeds, e.g., 60-120rpm, produces a three-phase

TABLO LİSTESİ

Tablolar

variable AC voltage, \$310V\$ to \$600V\$ line-to-line, at a frequency of \$6-12Hz\$ and at a rated power of \$20kW\$ for some operating points. If a relatively heavy longitudinal PM generator or a transversal PM generator is used, the gear box between the turbine and the PM generator can be eliminated, resulting in reduced weight requirements for the tower. Three-phase AC voltage is then fed to the rectifier operating at slightly leading input power factor to produce a nearly constant DC voltage independent of input voltage amplitude and frequency variations and load changes. A current-controlled PWM inverter then converts the DC voltage to three-phase AC currents at a system line-to-line voltage of 240V. The output frequency of the inverter is locked to the nominal power-grid frequency of \$60Hz\$. The amplitude and the phase of the AC current fed into the power system are controllable through the adjustment of the three-phase reference currents, resulting in powers delivered at leading and lagging power factors to the power system. To provide an isolation and to ease the testing of the entire system, a three-phase transformer is placed between the inverter and the power grid. In later applications such a transformer can be omitted.

The total installed capacity of wind power plants has reached about 1.8 GW in North America in 1994 \cite{ti}. Most of these plants employ induction generators with a speed-up gear operating at nearly constant speed. There is no direct-drive variable-speed wind power train of this type on the market yet. Therefore, the work of this dissertation and the prior work \cite{batan} to \cite{batan} can be considered to be novel and the first of its type.

\chapter{CONCLUSIONS}

A direct drive train for a wind power plant without any mechanical gear, operating at variable speeds (60-\$120rpm\$) can extract more power from wind than a constant speed drive. Any voltage fluctuations (300-\$600 V_{L-L}\$) on the generator side as the wind velocity changes will permit the drive train to remain on-line, because the rectifier maintains a constant DC link voltage (\$360 V_{DC}\$). The real and reactive powers delivered to the utility system are adjustable by changing the amplitude and phase angle of the reference current signals of the inverter. Therefore, leading, lagging, and unity currents (with respect to voltage) can be supplied. However, higher DC voltages (about \$V_{DC}=450VDC\$) are required to supply lagging currents as compared to the operation with leading currents (\$V_{DC}=350VDC\$). Since the input voltage to the inverter is fixed by the rectifier at around \$V_{DC}=360VDC\$, this drive train can deliver power to the utility system at unity or leading power factors only.

The losses of inductors as a function of frequency (0 to \$6 kHz\$) have been measured using two different approaches (computer-aided and three-voltmeter methods). Errors of both methods are less than 10\% when measuring a fraction of one watt. It has been found that inductors wound with Litz wires have the lowest losses and the value of the inductance reduces slightly with the frequency. A stranded straight wire, where the individual strands are not insulated and proximity effects due to a wound coil do not exist, has larger losses than a solid straight wire if both wires have the same cross-sectional area. This is due to an effect called ``spiral effect'' caused by the stranding.

Existing formulations of the distortion power D have been reviewed as a function of voltage and current harmonic amplitudes and phase angles. The correct double trigonometric sum for the definition of D, given by Equation , is not similar to (with respect to

the indices of the double sum) existing formulations which are not quite correct, neither from a numerical nor a physical point of view, due to the involvement of like voltage and current components in D. Experimental results agree well with the results obtained by using individual voltage and current harmonics. If distortion power exists in a system, it increases the rms current and as a result additional losses are produced; usual compensation techniques cannot be applied to reduce the distortion power in a system. Any compensation must be based either on filtering of harmonics or injecting harmonics to the power system.

The derating of a single-phase transformer in the presence of nonsinusoidal voltages and currents is measured using a computer-aided testing circuit. Measured results are compared with results obtained by using K -factor and F_{HL} -factor approaches. It has been found that the K -factor (favored by UL) derating is somewhat larger than that of F_{HL} -factor (favored by IEEE) derating as applied to a 25kVA transformer. Capacitors connected across the DC side of rectifiers have an influence on the derating of transformers since they increase the input voltage and decrease the required input current of an apparent power rated transformer resulting in less severe derating values. The other stray losses in enclosures, clamps and nearby conductive regions due to changing fluxes have a maximum value at a certain frequency, depending on the type of material used. Up to this frequency, losses increase with a power of 0.8 of frequency $(f_h/f_1)^{0.8}$, and further increase of the frequency results in a decrease of the losses with a power of 0.9 of frequency $(f_h/f_1)^{0.9}$.

\section{Contribution of this Thesis}

\begin{itemize}

%
\item The experimental testing of the rectifier and the PWM inverter which are components of a 30 kVA variable-speed, direct-drive wind power plant and the operation of the entire drive system, that is synchronous generator, rectifier and inverter connected to the utility system, are presented.

%
\item The 20kW zero-current-switch (ZCS) rectifier employs one switching transistor to control the output voltage to be nearly constant for variable input voltage and variable frequency. Such a large rating ZCS rectifier has not yet been designed and built.

%
\item Reactive-power controllability of the inverter was studied. It has been found that for a given DC input voltage, leading and unity-power factor operations are easily obtained, but for lagging power factor operations the DC input voltage must be increased substantially.

%
\item For a given DC input voltage, the AC output voltage of the inverter can be increased by operating the inverter in overmodulation mode ($m > 1.0$). This overmodulation is achieved by introducing, for all operating conditions, an additional lagging phase shift between the reference currents and the (actual) output currents of the inverter.

%
\item An accurate measurement of frequency-dependent losses of inductors by use of two different methods are presented. The results obtained from the two measurements agree well with each other, and each method can measure a fraction of a watt with a maximum error of less than 10% over a large frequency range (0-6kHz).

%
\item A transverse-flux type permanent magnet machine is investigated for applications to high-power wind generation because of its light weight compared to those of conventional

ÖZET

Most wind turbines in service today employ induction generators together with a step-up mechanical gear so that the operational speed is close to the synchronous speed of two or four-pole generators. Because of the torque-speed characteristic of induction generators, the range of speed change is rather small; therefore, the operational speed can be considered to be nearly constant. Mechanical gears are subject to wear and tear, reduce reliability of the drive train and add to its weight. The maximum power that can be extracted from wind varies with its speed. Therefore, a direct-drive system, where a wind turbine is directly coupled to the generator shaft, is desirable along with a variable-speed operation.

The variable-speed, direct-drive train described in this thesis consists of a low-speed, permanent-magnet generator (60 to 120rpm), a resonant rectifier and a pulse-width-modulated inverter. It supplies 30kVA/20kW apparent/real power to the utility system at leading and unity power factors for a given DC link voltage. The amplitude and phase (leading, unity) of the AC current delivered to the utility system are controllable and the voltage/current wave forms at the point of common coupling satisfy standard IEEE-519. The overall efficiency of the drive train is about 83% (excluding the generator), whereby the rectifier has an efficiency of 86% and the inverter efficiency is around 95%.

Using two different approaches (computer-aided and three-voltmeter methods), the losses of inductors are measured for the frequency range of 0 to 6kHz. Measurement errors of both methods are less than 10% when measuring a few watts. The AC resistance increase of a Litz-wire inductor without a core is smallest among all of the inductors being tested. Stranding of individual (uninsulated) wires to obtain a flexible cable results in more losses than using a solid cable having the same cross-sectional area as that of a stranded cable.

Nonsinusoidal voltages and currents in a power system can produce an additional power, called distortion power, generated from the cross products of voltage and current harmonics of different frequencies. This additional power increases system losses that cannot be easily compensated. Existing definitions of distortion power are not quite correct either from a numerical or a physical point

longitudinal-type generators.

%
\end{itemize}

\section{Further Work}

Generation of electricity from wind has been increasing steadily (about \$10\%) with the installation of new wind farms each year. However, installed capacity of wind farms is still low (\$7 GW) compared to the total installed (\$700 GW) power capacity in the United States. Wind farms consist of a great number (typically hundreds) of small (\$100 kW to \$1 MW) wind turbines operating at constant speed (\$30 rpm). Use of variable speed enables the wind turbine to operate more energy-efficient at different wind speeds; therefore, somewhat more energy can be extracted from the wind. It is desirable to increase the power rating of an individual wind turbine so that larger amounts of power can be generated by one unit. One of the problems associated with increasing power of one unit is the increase of weight (generator and gear box) on the tower.

%
\begin{itemize}

%
\item This problem may partially be solved by employing a transverse-flux type generator which offers a light weight for high torques at low speeds, therefore, more work should be done to completely study the transversal-flux type machines for such an application.

%
\item Since the variable-speed type system employs expensive power semiconductor devices, a cost analysis should be performed to determine the effectiveness of this type of drive system and rectifier; inverter and machine efficiencies should be in the range from 98 to 99\%.

%
\item High-efficiency converter (rectifier/inverter) losses should be measured with small maximum errors (3\%).

%
\end{itemize}

% KAYNAKLAR
% Kaynaklar kısmi buradan baslamaktadır. Her kaynaga ait bir
% tanıtıcı ifade yazmanız gerekiyor (örnek \bibitem{tanıtıcı}).
% Metin içinde bu kaynaga atıf yapmak istediğiniz zaman
% \cite{tanıtıcı} komutunu kullanıyorsunuz

%
\begin{thebibliography}{99}

\bibitem{fuchs3} E. F. Fuchs, A. A. Fardoun, P. W. Carlin, and R. W.

Erickson, "Permanent-Magnet Machines for Operation with Large Speed Variations," *Proceedings of Windpower 1992*, Seattle, WA, October 19-23, 1992.

\bibitem{ti} Motorola FAST and LS TTL Data Book, DL121/D, 5th edition, 1992.

\bibitem{iec55} CEI/IEC *Standard 555*, Bureau Central de la Commission Electrotechnique Internationale 3, rue de Varembe, Genève, Switzerland.

\bibitem{mohan} N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics, Converters, Applications and Design*, 2nd Ed., John Wiley & Sons, 1995.

of view because they involve voltage and current harmonics of the same frequency; therefore, a correct formulation is given which agrees well with experimental results.

When a transformer is operating under nonsinusoidal voltages and currents, its apparent power output must be reduced (derating) in order not to exceed the rated temperature. Comparison of measured derating values with ones obtained from K - and F_{HL} -factor approaches reveals that the K -factor approach yields somewhat greater derating values than the F_{HL} -factor approach. The losses of conductive materials in the presence of magnetic fluxes are also investigated and it has been found that the maximum losses in these components occur at a specific (material-dependent) frequency. The losses are proportional to the power of 0.8 below this frequency and are inversely proportional to the power of 0.9 above this frequency.

\bibitem{batan} T. Batan, ``Real-Time Monitoring and Calculation of the Derating of Single-Phase Transformers under (Non)Sinusoidal Operations,'' {\it Ph.D. Thesis}, University of Colorado at Boulder, 1998.

\bibitem{yildirim} D. Yildirim and E.F. Fuchs, ``Computer-Aided Measurement of Inductor Losses at High Frequencies (0 to 6kHz),'' 14th Applied Power Electronics Conference and Exhibition, Dallas, TX, March 14-18, 1999.

\bibitem{c5718} {\it ANSI/IEEE Standard Practices and Requirements for Semiconductor Rectifier Transformers}, ANSI/IEEE C57.18.10-1998, Institute of Electrical and Electronics Engineers, Inc., New York, NY, 1998.

%
\end{thebibliography}

% KAYNAKLAR sona erdi

% Ekler basliyor

\appendix
\chapter{FORTRAN PROGRAM FOR FOURIER ANALYSIS}
%\newpage
\parskip .5cm
%\small{
\noindent{
\baselineskip 12pt
\begin{verbatim}

implicit complex(c)

c
c np=number of points (n+1) ; mp=number of harmonics (nh)
c
c parameter (np=82, mp=19)

c
real func(np),mt(np),fx(np),fxc(np),fxs(np),t(np)
real har(mp),phase(mp),norm(mp),fav(mp),fbv(mp)
common /fourier/ fk1,fk2,fk3,a1,a2,nt
common /trapez/ pi, n
open(unit=5,file='i21397-8.txt',status='unknown')
open(unit=11,file='fout.txt',status='unknown')

c
c n=number of data points(0 to n) in one period (0-2pi)
c nh=number of harmonics, sca=scale factor, dc=dc offset
c

nt=np
n=nt-1
nh=mp
sca=50./17.5
om=377.
pi=4.*atan(1.)

c
c coefficients for fourier analysis
c

p=sqrt(0.6)
a1=5./9.
a2=8./9.
fk1=0.5*p*(1.+p)
fk2=(1.+p)*(1.-p)
fk3=0.5*p*(p-1.)

c
c set up the time axis 0-2pi
c

d=2.*pi/(nt-1)
t1=-d

BÖLÜM 1

INTRODUCTION

During the past ten years of research, design and construction of a 30 kVA variable-speed (60 to 120rpm) direct-drive wind power plant has been conducted in the Department of Electrical and Computer Engineering of the University of Colorado at Boulder. Most support for this project [6] was provided by the National Renewable Energy Laboratory (NREL) in Golden. The primary work for design and construction of the low-speed permanent magnet generator is described in [5]. This generator has been extensively tested [4] and mounted on a tower at the National Wind Technology Center (NWTC) of NREL. The 30kVA three phase PWM (pulse-width-modulated) inverter has been tested on the bench and reported in [6] for output powers of 20kW at about unity-power factor, without employing a transformer between the inverter and the power system of Public Service Company of Colorado, and without final mounting of the components within a steel cabinet. The zero-current-switch resonant rectifier has been assembled and tested [6] on the bench up to 3.2kW at low input and output voltages without control of the output voltage, and the components did not work properly within the environment of a steel cabinet.

Preliminary results of the above work have been reported in [2], and two invention disclosures were submitted to the Office of Intellectual Resources and Technology Transfer of the University of Colorado at Boulder [3].

The goal of this dissertation was to resume the work on the design and testing of the individual components of this project - the resonant rectifier, the PWM inverter including the current control for real/reactive/apparent powers - and to make all components work together so that, for a variable turbine speed varying from 60 to 120 rpm, a variable power at constant nominal frequency (e.g., 60 Hz) and at constant nominal voltage (e.g., 240 V_{L-L}) is supplied to the utility system, whereby the current wave shapes including the displacement factor and current amplitude are controllable.

The work of this dissertation encompasses the following topics:

- (1) 20 kW Three-Phase, Zero-Current-Switch (ZCS) Resonant Rectifier.

```

do 10 i=1,nt
    t1=t1+d
10  t(i)=t1
c
c  reading input file(contains one set of data)
c  and writing the scaled data on file fort.20
c
    read(5,*) (func(i),i=1,nt)
    dc=func(1)
    do 21 i=1,nt
        mt(i)=(func(i)-dc)*sca
21  write(20,*)t(i),mt(i)
c
c  mt=time domain input (0-2pi), av=average value of mt
c  rms=rms value of mt
c
    call trap(mt,av,rms)
c
    print*,'dc component from trapezoidal=', av
    print*,'rms value from trapezoidal=', rms
c
c  mt=time domain input, fav,fbv = fourier coefficients
c
call harm(mt,nh,fav,fbv,dcoeff,t)
c
    ht=0.0
    fsq=0.0
    do 30 j=1,nh
        har(j)=sqrt(fav(j)**2 + fbv(j)**2)
        if (fbv(j).eq.0.0) then
            phase(j)=0.0
        else
            phase(j)=atan(fav(j)/fbv(j))
        end if
        if (fbv(j).lt.0.00) phase(j)=phase(j)+pi
        if (j.eq.1) then
            hfund=har(j)
        else
            ht=ht + har(j)**2
        endif
        norm(j)=har(j)/hfund*100
        fsq=fsq + (har(j)/sqrt(2.))**2
30  continue
    thd=sqrt(ht)/hfund*100
    frms=sqrt(fsq)
cc
    write(11,*)'*****'
    write(11,*)'dc component=',dcoeff
    write(11,*)'dc component from trapezoidal=', av
    write(11,*)'rms value from trapezoidal=', rms
    write(11,*)'-----'
    write(11,*)
    write(11,1)
1  format(7x,1hh,5x,9hamplitude,4x,
&      7hnorm(%),5x,10hphase(deg),/)
    do 40 j=1,nh
40  write(11,2)j,har(j),norm(j),phase(j)*180/pi
2  format(6x,i3,4x,e11.5,2x,f10.6,2x,f10.6,2x,f10.6)
    write(11,*)'*****'
    write(11,*)'total harmonic distortion =',thd,'% '
    write(11,*)'rms value of the waveform =',frms
    write(11,*)'rms of the fundamental =',hfund/sqrt(2.)
    write(6,*)'total harmonic distortion =',thd,'% '
    write(6,*)'rms value of the waveform =',frms
    write(6,*)'rms of the fundamental =',hfund/sqrt(2.)
c

```

- Redesign of the input filter for higher voltage (600V) and current (40A) stresses. A damping network is also added to the input filter.
- Series connection of input bridge diodes to accommodate higher voltage (2000V) stresses.
- Redesign of tank diodes and transistor (IGBT, insulated-gate-bipolar transistor) for higher voltage (1400V) and current (200A) stresses.
- Design of the control circuit providing constant DC output voltage (e.g., 360 V) at variable AC input voltage (e.g., 300 V_{L-L} to 600 V_{L-L})
- Mounting of rectifier components within a steel cabinet, and solution of EMI (electromagnetic interference) problems.
- Debugging of the rectifier to deliver, at rated inputs, the rated output quantities.

(2) 30 kVA Three-Phase Current-Controlled PWM Inverter.

- Employment of a three-phase transformer between inverter and power system.
- Debugging of the phase-lock-loop and gating circuits and to improve their operating stability.
- Addition of a harmonic tuned filter at the point of common coupling (PCC) to reduce the high frequency harmonic current flowing into the power system and to obtain a sinusoidal voltage waveform at the output of inverter before connecting it to the power system.
- Before connecting to the utility system, the required AC sinusoidal output voltage ($260V_{L-L}$ AC) for a given DC input voltage (340V DC) can be obtained by operating the PWM inverter with a modulation index greater than 1 ($m > 1$) – independent of the operating point of the inverter. This operating mode is novel: it improves the sinusoidal wave shape of the inverter output voltage and current, reduces switching losses, and reduces the input DC voltage required when compared to PWM with $m < 1$.
- Introduction of a phase-shifting input transformer, to make the displacement power factor of the inverter adjustable.
- Mounting the inverter components within a steel cabinet and to remove parasitic EMI problems.

```

c      construct original function from fourier coefficients
c      and write result to file fort.21
c
do 55 i=1,nt
  fx(i)=0.0
  do 56 j=1,nh
    h=float(j)
    fxc(i)=fav(j)*cos(h*t(i))
    fxs(i)=fbv(j)*sin(h*t(i))
c      write(12,*)h,fav(j),fxc(i),fxs(i)
    fx(i)=fx(i)+fxc(i)+fxs(i)
56    continue
55  continue
c      do 58 i=1,nt
c58    write(21,*)t(i),fx(i)
c
c      stop
c      end

c      work: time domain input
c      tt: time axis input
c      dcc: computed dc offset of work (output)
c      idh: number of harmonics input
c      avc,bvc: fourier coefficients (output)

subroutine harm(work,idh,avc,bvc,dcc,tt)
implicit complex(c)
tp=b-a
sum=0.0
do 90 i=2,n
sum=sum+f(i)
90  continue
fave=(1/tp)*0.5*h*(f(1)+f(n+1)+2*sum)
do 91 i=1,n+1
fkare(i)=f(i)**2
91  rsum=0.0
do 92 i=2,n
rsum=rsum+fkare(i)
92  rint=(1/tp)*0.5*h*(fkare(1)+fkare(n+1)+2*rsum)
frms=sqrt(rint)
return
end
\end{verbatim}
}

% Ekler sona erdi
\end{document}

```

- Establishing control surfaces for apparent power S and real power P as a function of the reference-current signal $V_{I_{ref}}$ varying between 0.9V and 7V.
 - The real and reactive power flow generated by the PWM inverter and fed into the utility system is investigated using fundamental and harmonic phasor analyses.
- (3) Joint operation of the ZCS rectifier and the PWM inverter – mounted in steel cabinets – delivering rated power to the utility system.
 - (4) Conceptual design of a Transversal Flux Machine (either motor or generator), providing high torques (5 kNm to 2.5 kNm) at low speeds (60 rpm to 120 rpm) based on alternating magnetic field theory. The work of [2] has been extended and two invention disclosures have been submitted [3].
 - (5) In a circuit where the load is nonlinear or the source has nonsinusoidal quantities, the apparent power is not simply $S = \sqrt{P^2 + Q^2}$: another type of power called distortion power (D) is generated by the cross products of voltage and current harmonics of different frequencies. For nonsinusoidal voltages and currents the apparent power is defined as $S = \sqrt{P^2 + Q^2 + D^2}$. This additional power D increases the load current (apparent power S gets larger) and causes additional losses. Past definitions of the distortion power are reviewed and most are found not to be correct either from a numerical or physical point of view. A proper formulation is derived for the computation of D from the individual voltage and current harmonics not containing voltages and currents of the same frequency. Experiments are performed to measure the distortion power for a variety of load conditions, i.e., for different THD_i and THD_v values.
 - (6) Measurement of losses of inductors employed in different parts of the drive system, using two different approaches. Two methods for measuring losses of inductors at frequencies from 0 to 6kHz are discussed; the first involves the use of sampled inductor voltage and current wave forms through an A/D converter and a computer. The second, called three-voltmeter method, consists of recording the rms values of three sinusoidal voltages. Error analyses of the two approaches are presented.
 - (7) Measurement of the derating of single-phase transformers operating at nonsinusoidal voltage and current wave forms, and comparison of the

measured derating values with those obtained from K-factor and harmonic-loss factor (F_{HL}) approaches.

In the following it is assumed that the reader is familiar with the primary references of this work [6] to [5] and an effort will be made to complement and if necessary correct the statements and ideas of these references - thus repetition will be avoided.

Many of today's wind turbines employ standard, off-the-shelf induction generators, along with a step-up mechanical gear operating at nearly constant speeds. Mechanical gears are subjected to wear and tear, are expensive, reduce reliability [5], reduce efficiency of the drive train and add to its weight. Therefore, in wind power generating plants, direct-drive trains without any mechanical gears are desirable. Figure 1.1 illustrates the power curve of a wind turbine at two

Şekil 1.1: Power versus wind speed at two different rotor speeds [6].

different wind speeds [6], where the output power of the wind turbine for a given wind speed peaks to a maximum value. Therefore, by allowing the rotor speed to vary with the wind speed, wind turbines can extract the maximum power available at different wind speeds [5].

Figure 1.2 shows the schematic diagram of a variable-speed, direct-drive

Şekil 1.2: 30 kVA variable-speed, direct-drive wind power plant.

wind power plant. The permanent magnet (PM) generator operating at low speeds, e.g., $60 - 120rpm$, produces a three-phase variable AC voltage, $310V$ to $600V$ line-to-line, at a frequency of $6 - 12Hz$ and at a rated power of $20kW$ for some operating points. If a relatively heavy longitudinal PM generator or a transversal PM generator is used, the gear box between the turbine and the PM generator can be eliminated, resulting in reduced weight requirements for the tower. Three-phase AC voltage is then fed to the rectifier operating at slightly leading input power factor to produce a nearly constant DC voltage independent of input voltage amplitude and frequency variations and load changes. A current-controlled PWM inverter then converts the DC voltage to three-phase AC currents at a system line-to-line voltage of $240V$. The output frequency of the inverter is locked to the nominal power-grid frequency of $60Hz$. The amplitude and the phase of the AC current fed into the power system are controllable through the adjustment of the three-phase reference currents, resulting in powers delivered at leading and lagging power factors to the power system. To provide an

isolation and to ease the testing of the entire system, a three-phase transformer is placed between the inverter and the power grid. In later applications such a transformer can be omitted.

The total installed capacity of wind power plants has reached about $1.8GW$ in North America in 1994 [2]. Most of these plants employ induction generators with a speed-up gear operating at nearly constant speed. There is no direct-drive variable-speed wind power train of this type on the market yet. Therefore, the work of this dissertation and the prior work [5] to [5] can be considered to be novel and the first of its type.

BÖLÜM 2

CONCLUSIONS

A direct drive train for a wind power plant without any mechanical gear, operating at variable speeds (60-120rpm) can extract more power from wind than a constant speed drive. Any voltage fluctuations (300-600V_{L-L}) on the generator side as the wind velocity changes will permit the drive train to remain on-line, because the rectifier maintains a constant DC link voltage (360V_{DC}). The real and reactive powers delivered to the utility system are adjustable by changing the amplitude and phase angle of the reference current signals of the inverter. Therefore, leading, lagging, and unity currents (with respect to voltage) can be supplied. However, higher DC voltages (about V_{DC} = 450VDC) are required to supply lagging currents as compared to the operation with leading currents (V_{DC} = 350VDC). Since the input voltage to the inverter is fixed by the rectifier at around V_{DC} = 360VDC, this drive train can deliver power to the utility system at unity or leading power factors only.

The losses of inductors as a function of frequency (0 to 6kHz) have been measured using two different approaches (computer-aided and three-voltmeter methods). Errors of both methods are less than 10% when measuring a fraction of one watt. It has been found that inductors wound with Litz wires have the lowest losses and the value of the inductance reduces slightly with the frequency. A stranded straight wire, where the individual strands are not insulated and proximity effects due to a wound coil do not exist, has larger losses than a solid straight wire if both wires have the same cross-sectional area. This is due to an effect called “spirality effect” caused by the stranding.

Existing formulations of the distortion power D have been reviewed as a function of voltage and current harmonic amplitudes and phase angles. The correct double trigonometric sum for the definition of D, given by Equation, is not similar to (with respect to the indices of the double sum) existing formulations which are not quite correct, neither from a numerical nor a physical point of view, due to the involvement of like voltage and current components in D. Experimental results agree well with the results obtained by using individual voltage and current

harmonics. If distortion power exists in a system, it increases the rms current and as a result additional losses are produced; usual compensation techniques cannot be applied to reduce the distortion power in a system. Any compensation must be based either on filtering of harmonics or injecting harmonics to the power system.

The derating of a single-phase transformer in the presence of nonsinusoidal voltages and currents is measured using a computer-aided testing circuit. Measured results are compared with results obtained by using *K*-factor and *F_{HL}*-factor approaches. It has been found that the *K*-factor (favored by UL) derating is somewhat larger than that of *F_{HL}*-factor (favored by IEEE) derating as applied to a 25kVA transformer. Capacitors connected across the DC side of rectifiers have an influence on the derating of transformers since they increase the input voltage and decrease the required input current of an apparent power rated transformer resulting in less severe derating values. The other stray losses in enclosures, clamps and nearby conductive regions due to changing fluxes have a maximum value at a certain frequency, depending on the type of material used. Up to this frequency, losses increase with a power of 0.8 of frequency (f_h/f_1)^{0.8}, and further increase of the frequency results in a decrease of the losses with a power of 0.9 of frequency (f_h/f_1)^{0.9}.

2.1 Contribution of this Thesis

- The experimental testing of the rectifier and the PWM inverter which are components of a 30 kVA variable-speed, direct-drive wind power plant and the operation of the entire drive system, that is synchronous generator, rectifier and inverter connected to the utility system, are presented.
- The 20kW zero-current-switch (ZCS) rectifier employs one switching transistor to control the output voltage to be nearly constant for variable input voltage and variable frequency. Such a large rating ZCS rectifier has not yet been designed and built.
- Reactive-power controllability of the inverter was studied. It has been found that for a given DC input voltage, leading and unity-power factor operations are easily obtained, but for lagging power factor operations the DC input voltage must be increased substantially.
- For a given DC input voltage, the AC output voltage of the inverter can be increased by operating the inverter in overmodulation mode ($m > 1.0$). This overmodulation is achieved by introducing, for all operating condi-

tions, an additional lagging phase shift between the reference currents and the (actual) output currents of the inverter.

- An accurate measurement of frequency-dependent losses of inductors by use of two different methods are presented. The results obtained from the two measurements agree well with each other, and each method can measure a fraction of a watt with a maximum error of less than 10% over a large frequency range (0-6kHz).
- A transverse-flux type permanent magnet machine is investigated for applications to high-power wind generation because of its light weight compared to those of conventional longitudinal-type generators.

2.2 Further Work

Generation of electricity from wind has been increasing steadily (about 10%) with the installation of new wind farms each year. However, installed capacity of wind farms is still low (7GW) compared to the total installed (700GW) power capacity in the United States. Wind farms consist of a great number (typically hundreds) of small (100kW to 1MW) wind turbines operating at constant speed (30rpm). Use of variable speed enables the wind turbine to operate more energy-efficient at different wind speeds; therefore, somewhat more energy can be extracted from the wind. It is desirable to increase the power rating of an individual wind turbine so that larger amounts of power can be generated by one unit. One of the problems associated with increasing power of one unit is the increase of weight (generator and gear box) on the tower.

- This problem may partially be solved by employing a transverse-flux type generator which offers a light weight for high torques at low speeds, therefore, more work should be done to completely study the transversal-flux type machines for such an application.
- Since the variable-speed type system employs expensive power semiconductor devices, a cost analysis should be performed to determine the effectiveness of this type of drive system and rectifier; inverter and machine efficiencies should be in the range from 98 to 96%.
- High-efficiency converter (rectifier/inverter) losses should be measured with small maximum errors (3%).

KAYNAKLAR

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EK A

FORTRAN PROGRAM FOR FOURIER ANALYSIS

```

c
c      implicit complex(c)
c
c      np=number of points (n+1) ; mp=number of harmonics (nh)
c
c      parameter (np=82, mp=19)
c
c      real func(np),mt(np),fx(np),fxc(np),fxs(np),t(np)
c      real har(mp),phase(mp),norm(mp),fav(mp),fbv(mp)
c      common /fourier/ fk1,fk2,fk3,a1,a2,nt
c      common /trapez/ pi, n
c      open(unit=5,file='i21397-8.txt',status='unknown')
c      open(unit=11,file='fout.txt',status='unknown')
c
c      n=number of data points(0 to n) in one period (0-2pi)
c      nh=number of harmonics, sca=scale factor, dc=dc offset
c
c      nt=np
c      n=nt-1
c      nh=mp
c      sca=50./17.5
c      om=377.
c      pi=4.*atan(1.)
c
c      coefficients for fourier analysis
c
c      p=sqrt(0.6)
c      a1=5./9.
c      a2=8./9.
c      fk1=0.5*p*(1.+p)
c      fk2=(1.+p)*(1.-p)
c      fk3=0.5*p*(p-1.)
c
c      set up the time axis 0-2pi
c
c      d=2.*pi/(nt-1)
c      t1=-d
c      do 10 i=1,nt
c          t1=t1+d
10      t(i)=t1
c
c      reading input file(contains one set of data)

```

```

c      and writing the scaled data on file fort.20
c
c      read(5,*)(func(i),i=1,nt)
c      dc=func(1)
c      do 21 i=1,nt
c          mt(i)=(func(i)-dc)*sca
21      write(20,*)t(i),mt(i)
c
c      mt=time domain input (0-2pi), av=average value of mt
c      rms=rms value of mt
c
c      call trap(mt,av,rms)
c
c      print*,'dc component from trapezoidal=', av
c      print*,'rms value from trapezoidal=', rms
c
c      mt=time domain input, fav,fbv = fourier coefficients
c
c      call harm(mt,nh,fav,fbv,dc,off,t)
c
c      ht=0.0
c      fsq=0.0
c      do 30 j=1,nh
c          har(j)=sqrt(fav(j)**2 + fbv(j)**2)
c          if (fbv(j).eq.0.0) then
c              phase(j)=0.0
c          else
c              phase(j)=atan(fav(j)/fbv(j))
c          end if
c          if (fbv(j).lt.0.00) phase(j)=phase(j)+pi
c          if (j.eq.1) then
c              hfund=har(j)
c          else
c              ht=ht + har(j)**2
c          endif
c          norm(j)=har(j)/hfund*100
c          fsq=fsq + (har(j)/sqrt(2.))**2
30      continue
c      thd=sqrt(ht)/hfund*100
c      frms=sqrt(fsq)
c
c      write(11,*)'*****'
c      write(11,*)'dc component=',dc,off
c      write(11,*)'dc component from trapezoidal=', av
c      write(11,*)'rms value from trapezoidal=', rms
c      write(11,*)'-----'
c      write(11,*)
c      write(11,1)
1      format(7x,1hh,5x,9hamplitude,4x,
c      & 7hnorm(%),5x,10hphase(deg),/)
c      do 40 j=1,nh
c      write(11,2)j,har(j),norm(j),phase(j)*180/pi
2      format(6x,i3,4x,e11.5,2x,f10.6,2x,f10.6,2x,f10.6)
c      write(11,*)'*****'
c      write(11,*)'total harmonic distortion =',thd,'%
c      write(11,*)'rms value of the waveform =',frms
c      write(11,*)'rms of the fundamental =',hfund/sqrt(2.)
c      write(6,*)'total harmonic distortion =',thd,'%

```

```

write(6,*)'rms value of the waveform =' ,frms
write(6,*)'rms of the fundamental =' ,hfund/sqrt(2.)
c
c   construct original function from fourier coefficients
c   and write result to file fort.21
c
do 55 i=1,nt
  fx(i)=0.0
  do 56 j=1,nh
    h=float(j)
    fxc(i)=fav(j)*cos(h*t(i))
    fxs(i)=fbv(j)*sin(h*t(i))
c     write(12,*)h,fav(j),fxc(i),fxs(i)
    fx(i)=fx(i)+fxc(i)+fxs(i)
56   continue
55   continue
c   do 58 i=1,nt
c58  write(21,*)t(i),fx(i)
c
c     stop
c     end

c   work: time domain input
c   tt: time axis input
c   dcc: computed dc offset of work (output)
c   idh: number of harmonics input
c   avc,bvc: fourier coefficients (output)

subroutine harm(work,idh,avc,bvc,dcc,tt)
implicit complex(c)
tp=b-a
sum=0.0
do 90 i=2,n
sum=sum+f(i)
90  continue
fave=(1/tp)*0.5*h*(f(1)+f(n+1)+2*sum)
do 91 i=1,n+1
fkare(i)=f(i)**2
91  rsum=0.0
do 92 i=2,n
rsum=rsum+fkare(i)
92  rint=(1/tp)*0.5*h*(fkare(1)+fkare(n+1)+2*rsum)
frms=sqrt(rint)
return
end

```