DESIGN AND DEVELOPMENT OF VOLTAGE AND FREQUENCY CONTROLLERS FOR SINGLE-PHASE SELF EXCITED INDUCTION GENERATORS

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by

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CERTIFICATE

This is to certify that the thesis entitled, "**Design and Development of Voltage and Frequency Controllers for Single-Phase Self Excited Induction Generators**" being submitted by **Mr. Ujjwal Kumar Kalla** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Ujjwal Kumar Kalla has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other university or Institute for the award of any degree.

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Date Ujjwal Kumar Kalla

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ABSTRACT

This thesis investigates the use of a two winding single phase self excited induction generator (SEIG) for standalone off grid single-phase power generation using different renewable energy sources ether singly or in combinational hybrid mode. Various solid state controllers are explored and successfully implemented for each case. This is the first such attempt to use a specially designed two winding SEIG for renewable energy application to feed single-phase loads vastly prevalent in isolated and remote locations, in accessible to the grid. This research work assumes great importance due to the nonavailability of the power in remote regions in developing countries. Moreover, there is a need to exploit local renewable sources such as bio, hydro, wind, in combination with solar energy. Present global emphasis to generate pollution free electricity makes the work all the more important.

The first case deals with the controlled capacitor scheme wherein a fixed capacitor is used across an auxiliary winding and variable shunt capacitor is realized across the main winding in parallel with the load. The novelty is the back to back connected thyristor scheme with the main winding capacitor to smoothly vary the VAR through the control of thyristors. It is suitable with both resistive and inductive loads such as lighting, fans and heating loads which are linear static or dynamic loads. The hardware for this VAR controller has been designed and successfully implemented for SEIG. This scheme is found suitable for bio or diesel engine as a prime mover with varying speeds of about 20%.

The next scheme for control of SEIG deals with nonlinear loads typically rectifier loads used in PCs, laptops and IT equipments needed for remote communities to improve their connectivity. The scheme uses an H-bridge type IGBT based voltage source converters

(VSC) with a capacitor at its DC bus, in parallel with the loads to inject an adjustable harmonics and fundamental reactive VAR needed by SEIG and loads. It ensures that SEIG has minimum harmonics despite high THD (Total Harmonic Distortion) of the load current. This is also found suitable for engine driven systems.

An improvement of the above scheme is to obtain constant voltage and frequency across the loads with the above type of prime mover under linear and nonlinear loads. Here, the engine functions under a single point operation with constant output power, torque and speed. For feeding variable loads, the residual power is used to charge the battery to maintain constant output of the engine. Here, a VSC is used for voltage control with the VAR and harmonic mitigation while the battery works for frequency control with a real power balance.

The next scheme deals with a small-hydro generating system wherein the power may be constant in a given condition but it varies seasonably dependent on input water flow. The SEIG output frequency is maintained constant through a feedback mechanism using the reference frequency. A frequency error signal is used to trigger PWM pulses to the IGBT of an electronic load controller. Moreover, it in turn feeds suitable power to the dump load. With the constant load, the voltage remains constant through an equilibrium status.

An another scheme deals with the decoupled voltage and frequency controller (DVFC) of a SEIG driven by small uncontrolled hydro turbine wherein both voltage and frequency are separately regulated. Here, frequency error signal is fed to control a chopper IGBT to alter the dump load for constant frequency. The terminal voltage error signal, dc bus voltage error signal of VSC and load current are used in the proposed control algorithm which estimates the reference source current to regulate the load voltage.

The integrated voltage and frequency controller (IVFC) of a SEIG driven by small uncontrolled hydro turbine, is another scheme being investigated in detail. This is an improved scheme for small-hydro application. A further improvement is achieved through an additional battery storage energy system to the above. The series combination of chopper and dump load resistance of the previous IVFC scheme is replaced by a battery energy storage system (BESS). During varying load condition, the residual power is stored in the battery to maintain the system frequency. In overload condition, the additional power is supplied by the battery to maintain the system frequency. In the proposed control algorithm, the charging and discharging of the BESS are controlled by a frequency control loop with the frequency as a feedback variable, unlike auxiliary dump load based controllers, where the DC link voltage is used as a feedback variable.

The next control scheme of SEIG pertains to the wind energy application due to imperative need to have typical rooftop or isolated wind mills to supply single phase power using SEIG. This is a major breakthrough as PMSG are being implied for such applications. This is primarily a wind battery hybrid system with a dedicated control to operate at varying wind speeds. The voltage and frequency control of a wind turbine driven single phase SEIG under variable input power from wind turbine and at varying consumer loads is achieved using VSC-BESS. The VSC-BESS consists of a single-phase H-bridge type IGBT based voltage source converter and a battery energy storage system connected at its DC link.

The next stage of this research is towards creation of a single phase dedicated microgrid with a combination of renewable sources such as wind and hydro with a battery for power balancing. The scheme involves the DSP based integration of a standalone single phase SEIG based small hydro generating system with a wind energy conversion system based on PMBLDC generator. A VSC-BESS is used for active and reactive powers compensation of the micrgrid system which in turn controls the system voltage and frequency along with improved power quality.

Another variant of such a hybrid scheme is a hydro-solar system with a battery backup. It consists of microgrid system using a small hydro turbine driven single-phase SEIG integrated with solar PV-array. A sliding mode control based on susceptance theory is proposed which estimates the reference source current used to control the operation of multifunctional voltage source converter. The microgrid feeds all types of loads and ensures good power quality.

Finally, an integrated energy system as a combination of wind, hydro, bio and solar with a battery energy storage system has been developed. The scheme consists of three main renewable energy sources namely small-hydro, wind and solar PV array. The developed single-phase microgrid ensures the optimum utilization of the various renewable energy sources and BESS by integrating them. It also enhances the reliability of the system. The total required capacity of the BESS is significantly reduced in the microgrid system in comparison to individual power generating system, to obtain the same reliability. The proposed control algorithm regulates the system voltage and frequency, mitigates harmonic currents under variety of loads.

Thus, this thesis presents a comprehensive study of different modes of SEIG using renewable energy sources for single-phase power generation realizing the microgrid feeding a combination of practical loads with viable and successful controllers for each case to ensure desired quality power across the loads.

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LIST OF SYMBOLS

C_{sh}	Shunt capacitor
X_m	Magnetizing reactance
f	System Frequency
C_{aux}	Capacitor across the auxiliary winding
R_s	Stator main winding resistance
R_a	Auxiliary winding resistance
N_A/N_M	Auxiliary to main winding turns ratio
V_{min}	Terminal voltage setting provided in the controller
V_{ref1}	Desired minimum value of V_{min}
V_{ref2}	Desired maximum value of V_{max}
L_f	Interfacing inductor
C_{dc}	DC bus capacitor of VSC
S_{VSC}	kVA rating of VSC
R_D	Dump load resistor
Q_{SEIG}	Reactive power demanded by the SEIG
Q_{load}	Reactive power demanded by the load
V_t	Amplitude of PCC Voltage
V_{tRMS}	RMS value of PCC voltage
V_{ter}	Voltage error in PCC voltage
V_{tref}^*	Reference RMS value of PCC voltage
V_{dc}	DC-link voltage
V_{dc}^*	Reference value of DC-link voltage
V_{dce}	DC-link error voltage
u_p	In-phase unit template of the SEIG output voltage

u_q	Quadrature unit template of the SEIG output voltage
v_p	In-phase components of the PCC voltage
v_q	Quadrature components of the PCC voltage
i_s^*	Reference source current
i_s	Source current
i_{ser}	Source current error
hb	Width of hysteresis band
I_{dc}	DC side current
i_{VSC}	Rated VSC current
i_L	Load current
i_h	Harmonic current
i_M	Main winding current
i_A	Auxiliary winding current
i_L	Load current
I_D	Dump load current
ω	System frequency in rad/sec
m	Modulation index
f_{sw}	Switching frequency
a	Overloading factor
T	Time period
k_p	Proportional gain constant of the PI controller
k_i	Integral gain constant of the PI controller
X_c	Capacitive reactance
R_{deff}	Effective value of the dump load
G_{dc}	Instantaneous value of the conductance

G_{sp}	Total conductance
B_{v_t}	Instantaneous value of the susceptance
Q_L	Instantaneous value of reactive component of load
Q_{Ld}	DC component of instantaneous value of reactive power component of load
B_{Ld}	Instantaneous value of the susceptance of the load
B_{sq}	Total susceptance of the system
k	Sampling interval
G	Switching hyper plane function
h_1, h_2,	Constants of Sliding Mode Control
ξ_1, ξ_2	Constants of Sliding Mode Control
α	Learning rate
W_p	Weight of the active power component of single-phase load current
W_q	Weight of the reactive power constituent of the single-phase load
η	Learning or convergence constant
$\tilde{\eta}$	Learning rate
ΔW	Value of updated weight
$J(k)$	Cost function
β^*	Unknown complex valued Lagrange multiplier
$\|u(k)\|^2$	Squared Euclidean norm of unit input template of PCC voltage
N_r	Rotor speed
W_m	Amplitude of high frequency sawtooth carrier signal
V_{GE}	Collector-Emitter Voltage of IGBT
λ^*	Unknown complex valued Lagrange multiplier
Φ	Power factor angle
$\beta_f W_p$	Biasing component

β_f	Bias factor
ΔV_1	Bounce noise voltage

LIST OF ABBREVIATIONS

VFC	Voltage and Frequency Controller
SEIG	Self-Excited Induction Generator
TSC	Thyristor Switched Capacitors
SVC	Static Var Compensator
PWM	Pulse Width Modulated
IGBT	Insulated Gate Bipolar Transistors
ELC	Electronic Load Controller
DSP	Digital Signal Processor
BESS	Battery Energy Storage System
DG	Diesel Generator
PLL	Phase Lock Loop
PBC	PLL Based Controller
PCC	Point of Common Coupling
DVFC	Decoupled Voltage and Frequency Controller
VSC	Voltage Source Converter
IVFC	Integrated Voltage and Frequency Controller
FEPS	Frequency Estimation and Phase Shifting
PMBLDC	Permanent Magnet Brushless DC
PV	Photo Voltaic
RTW	Real Time Workshop
SOGI	Second Order Generalized Integrator
SRFT	Synchronous Reference Frame Theory
LMS	Least Mean Square
IRPT	Instantaneous Reactive Power Theory

DSTATCOM	Distribution Static Compensator
LPF	Low Pass Filters
APF	Active Power Filter
TCR	Thyristor Controlled Reactors
THD	Total Harmonic Distortion
TSR	Thyristor Switched Reactor
RMS	Root Mean Square
CMOS	Complementary Metal-Oxide Semiconductor
EMI	Electro Magnetic Interference
ZCD	Zero Crossing Detector
NABC	Normalized Adaptive linear element Based Control
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
VSI	Voltage Source Inverter
SMC	Sliding Mode Controller
ADALINE	Adaptive Linear Element
CF	Crest Factor
IEC	International Electro-technical Commission
IEEE	Institution of Electrical and Electronics Engineering
VFD	Voltage and Frequency Drive
PI	Proportional Integral
VCO	Voltage Controlled Oscillator
LMDT	Leaky Minimal Disturbance Theory
ANS	Adaptive Noise Suppression
LA	Leaky Adaline
HRC	High Rupturing Capacity

INNBC	Intelligent Neural Network Based Controller
MPPT	Maximum Power Point Tracking
WECS	Wind Energy Conversion System
CCM	Continuous Conduction Mode
ASMC	Adaptive Sliding Mode Control
HSF	Harmonic Suppression Filter
DVR	Dynamic Voltage Restorer