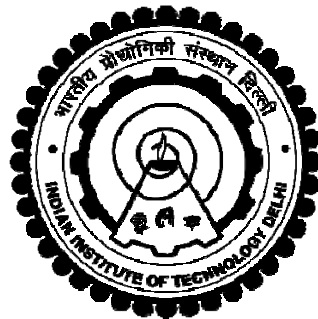


ANCILLARY SERVICES BY RENEWABLE ENERGY SOURCES

ZARINA.P.P



**DEPARTMENT OF ELECTRICAL ENGINEERING
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ANCILLARY SERVICES BY RENEWABLE ENERGY SOURCES

by

ZARINA. P.P

Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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OCTOBER 2016

CERTIFICATE

This is to certify that the thesis entitled “**Ancillary Services By Renewable Energy Sources**”, being submitted by **Ms. Zarina.P.P** for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by her in the Department of Electrical Engineering of the Indian Institute of Technology Delhi.

Ms. Zarina.P.P has worked under my supervision and guidance and has fulfilled the requirements for submission of this thesis, which to my knowledge has reached the requisite standard. The results recorded in this thesis has not been submitted in part or full for the award of any other degree or diploma.

Date:

Dr. Sukumar Mishra

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi – 16, India

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ABSTRACT

In many parts of the world much focus is given to the increase of renewable energy penetration. At least sixty seven countries, including twenty eight European Union (EU) countries have renewable energy policy targets of some type. When penetration of these sources increase drastically their integration to power system poses many challenges to the engineers. In order to ensure stability and reliability, grid codes are formulated by various countries. As per the grid codes, few ancillary service capabilities are expected from these renewable. This research work aims to enable the renewable sources to have the capability to provide ancillary services by using proper control strategies.

In order to have frequency regulation in a system, reserve is a requirement. So in the first phase of thesis, reserve is made available in photovoltaic systems by making use of the concept of deloading the PV. This reserve is made use of, for frequency regulation in a PV penetrated system. Three types of controllers, which includes a fuzzy logic controller for deloaded photovoltaic systems are suggested so that they have frequency regulation capability. For frequency regulation, the present practice is to use a battery along with a PV at its maximum power point of tracking. As it is proposed in this thesis to operate photovoltaics under deloaded conditions as reserve, without using battery, it is imperative to carry out a cost comparison. So in the second phase, a cost analysis of reserve offered by deloaded PV system is carried out and it is compared with the case of using a battery. Optimization technique was also applied to compare the cost from the perspective of overall cost components, including the cost of fuel consumption by conventional generators in the system.

The usefulness of deloaded PV in power fluctuation reduction between two areas is brought out. Another application highlighted was the frequency regulation aspect in a hybrid system consisting of PV and DFIG. The frequency disturbance due to the fall in wind speed was compensated by the reserve in the PV in the third phase of research.

As an independent power producer, all the sources, including the wind generators, are required to supply the scheduled power to the system as directed by the system operator, within a time frame of operation. The fluctuating nature of wind makes supplying the scheduled power a challenging task. To address this, gas turbines are proposed to augment the wind generator to work as buffer owing to their high ramping capability. However, the cost of gas turbine increases with increased ramp rates,

whereas, operating efficiency and the life time decreases. Hence, to relieve the buffering gas turbines from higher ramp rate requirements, in the last phase of this research work, emulation of inertia of the wind generator is proposed which reduces the ramping requirements of gas turbine. The wind generator is proposed to operate in inertia emulation mode during the disturbances and will be switched back to maximum power extraction mode once the system attains the steady state. While emulating the inertia, the performance of the proposed control philosophy with different ramp rates is investigated. Guide lines for the selection of the ramp duration and ramp rate for seamless transition from inertia emulation mode to maximum power extraction mode are also suggested.

TABLE OF CONTENTS

Sl. No.	Description	Page No.
	Certificate	i
	Acknowledgements	iii
	Abstract	v
	Table of contents	vii
	List of figures	xi
	List of tables	xv
	List of symbols	xvii
	List of abbreviations	xxi
Chapter 1	Introduction	1
1.1	Overview	1
1.2	Motivation	1
1.2.1	Policy formulation by government	3
1.2.2	Renewable energy targets around the world	5
1.2.3	Grid integration issues and related studies	5
1.2.4	Importance of ancillary service support by renewable sources	9
1.3	Research objectives	10
1.4	Organization of the thesis	11
Chapter 2	Integration Issues And Grid Code Requirements	15
2.1	Introduction	15
2.2	Grid codes around the world	16
2.2.1	Fault ride through capability curves	16
2.2.2	Extended voltage and frequency ranges	23
2.2.3	Reactive power support curves	25
2.2.4	Active power/ frequency regulation capability curves	29

2.3	Conclusion	31
Chapter 3	Frequency Control Capability of Deloaded PV	33
3.1	Introduction	33
3.2	Concept of reserve in photovoltaics	35
3.3	PV Modeling	36
3.4	Controller for frequency control contribution	38
3.5	Modified controller for distributed frequency control	39
3.6	Simulation results to show controller performance	40
3.6.1	Effect of controller parameter on PV power	41
3.6.2	Performance comparison of two types of controllers	43
3.6.3	Simulation results showing PV working under different conditions	44
3.7	PV with fuzzy logic controller for frequency regulation	46
3.7.1	Implementation of fuzzy controller	47
3.8	Conclusion	49
Chapter 4	Cost Analysis & Modes of Operation of Deloaded PV	51
4.1	Introduction	51
4.2	Cost comparison of two options for frequency regulation	51
4.2.1	Cost of additional panel providing reserve in case of deloaded PV	52
4.2.2	Cost of battery providing reserve in case of PV at MPPT	53
4.3	Modes of operation of deloaded PV	54
4.3.1	Mode 1-Extra reserve power in deloaded PV under higher irradiation	55
4.3.2	Mode 2- Deriving additional reserve by additional deloading	57
4.4	Optimization studies for cost analysis	58
4.4.1	System details	59
4.4.2	Base case	61

4.4.3	Conventional model with energy storage	62
4.4.4	Conventional model with PV	63
4.4.5	Comparison of cost of operation	64
4.5	Conclusion	65
Chapter 5	Deloaded PV for Power Oscillation Reduction and for Frequency Regulation in PV- DFIG Based Systems	67
5.1	Introduction	67
5.2	Power system oscillation	68
5.2.1	Controller for power fluctuation reduction	68
5.3	Frequency regulation in a hybrid PV-DFIG system	71
5.3.1	Wind turbine modeling	71
5.3.2	DFIG modeling	72
5.3.3	Simulation results	73
5.4	Conclusion	76
Chapter 6	Gas Assisted DFIG With Ramp Rate Controller	77
6.1	Introduction	77
6.2	Ramp rate limitation	78
6.3	System studied	80
6.3.1	Gas turbine	81
6.4	Ramp rate controller	82
6.4.1	Case1: Performance without using ramp rate controller	83
6.4.2	Case 2: Performance by using ramp rate controller	85
6.5	Results and discussions	87
6.5.1	Ramp controller for different ramp rates and with ramp duration of 10s	87
6.5.2	Ramp controller with proper selection of ramp duration	91
6.5.3	Performance of controller under different load conditions	93

6.5.4	Performance of controller under varying wind conditions	94
6.6	Conclusion	95
Chapter 7	Summary, Contributions and Future Scope	97
7.1	Summary of the present work	97
7.2	Contributions of the present work	99
7.3	Scope for future research	100
	References	101
	Appendices	107
	Publications and awards	113
	Bio-Data	115

LIST OF FIGURES

Fig. No.	Description	Page No.
2.1	LVRT limits specified by Danish grid code for voltage above 110kV	17
2.2	LVRT limits specified by Danish grid code for voltage below 100kV	17
2.3	LVRT limits specified by Belgium grid code	18
2.4	Comparison of LVRT curves of Hydro-Quebec and AESO	19
2.5	Spanish grid code requirements of LVRT	19
2.6	Italian grid code specification of LVRT	20
2.7	Swedish grid code requirements of LVRT	20
2.8	Australian HVRT Curve	21
2.9	LVRT requirement of Germany	22
2.10	LVRT requirement of Ireland and USA	22
2.11	UK's LVRT specification	23
2.12	Extended operation range according to Danish grid code	24
2.13	Allowed frequency- voltage variations as per Transpower grid code	25
2.14	Allowed frequency-voltage range as per Nordel grid code	25
2.15	Reactive current as per Danish Grid code	26
2.16	Danish grid code specification for reactive power and power factor requirement	26
2.17	Danish grid code specification for voltage regulation	27
2.18	Reactive power support requirement enforced by German grid code	28
2.19	Spanish grid code specification for reactive power requirement	28
2.20	Irish grid code specification of power –frequency response	30
2.21	Danish grid code specification of power-frequency response	31
3.1	Concept of reserve power in the PV array	36
3.2	PV model	36
3.3	Power Vs Voltage curve of PV array at different irradiation	37

3.4	Controller for deloaded PV without considering the amount of reserve	38
3.5	PV with higher deloading giving more reserve	39
3.6	PV with lesser deloading giving less reserve	39
3.7	Improved controller for deloaded PV which considers the amount of available reserve	40
3.8	Multi bus system layout considered for study	41
3.9	Variation in output power of photovoltaic with different values of K_i	41
3.10	Power output of conventional generator for different values of PV controller parameters	42
3.11	Comparison of system frequency for different values of PV controller parameters	42
3.12	PV power contribution with unequal reserve using controller considering frequency deviation alone	43
3.13	PV power contribution with unequal reserve using controller which considers frequency deviation and reserve	43
3.14	PV power under case 1 operation	44
3.15	Conventional generator power under case 1 operation	45
3.16	PV power under case 2 operation	45
3.17	Conventional generator power under case 2 operation	45
3.18	Fuzzy block representaion of Input and Output	48
3.19	Matlab – DIgSILENT integration block	48
3.20	Power increase of PV due to increased load demand	49
4.1	Reserve power variation with time	57
4.2	At lower irradiation, deloading more for higher reserve	58
4.3	System layout of six bus system	59
4.4	Load profile	62
4.5	Optimized result by using battery	63
4.6	PV availability profile	64
4.7	On-off state of different generators	64
4.8	Optimized result by using PV and no battery	64

5.1	Controller for power fluctuation reduction	69
5.2	Frequency fluctuation between the conventional generators	70
5.3	Power variation of PV	70
5.4	Wind turbine model	71
5.5	Pitch angle control model	72
5.6	Schematic block diagram of DFIG	73
5.7	Power Out of DFIG due to a fall in wind speed	73
5.8	PV power when working at MPP	74
5.9	Conventional generator power output	74
5.10	Frequency plot when no frequency regulation contribution from PV	74
5.11	PV power when working with the controller	75
5.12	Conventional generator power output when PV has the controller	75
5.13	Frequency plot when PV has the controller	76
6.1	Schematic diagram of the system considered	81
6.2	Set power of gas turbine	81
6.3	Ramp rate controller	83
6.4	Case:1 Path A-B-C followed by turbine power	84
6.5	a)Rotor speed Vs time b)Power Vs time for case 1	84
6.6	Mechanical power of turbine without ramp controller	84
6.7	Case:2 Path A-B-C-D-C followed by reference power	85
6.8	Mechanical power of turbine when ramp controller is used	86
6.9	Rotor speed variation while using ramp rate controller	86
6.10	P- ω characteristics for three different ramp rates with 10s ramp duration	88
6.11	Rotor speed variation with different values of ramp rate and a fixed ramp duration of 10s	88
6.12	DFIG power variation for different ramp rates and with ramp duration of 10s	90

6.13	Gas turbine power variation for different ramp rates and with ramp duration of 10s	90
6.14	Total power at PCC for a ramp duration of 10s (0.06pu/s ramp rate case)	91
6.15	P- ω characteristics with proper selection of ramp duration	91
6.16	Gas turbine power variation with proper selection of ramp duration	92
6.17	Mechanical power variation of wind turbine with controller	92
6.18	Rotor speed variation of wind turbine with controller	93
6.19	Total power at PCC for properly chosen ramp duration (0.06pu/s ramp rate case)	93
6.20	Performance of controller under varying loads	94
6.21	Real Wind profile for 12hrs	94
6.22	Performance of controller under real wind profile for first half an hour of Fig.6.21	95

LIST OF TABLES

Table. No.	Description	Page No.
1.1	Status of total power from renewable sources all over the world	2
2.1	Frequency limits in various international grid codes	24
3.1	Fuzzy rule characterized by membership functions	47
4.1	\$/watt cost of PV	52
4.2	Extra financial burden due to additional panel	52
524.3	Cost for using batteries of 2 years life span, with different sizes	53
4.4	11 MW PV Deloaded to provide a reserve	55
4.5	4.5 PV system at MPPT which gives 10MW power at 000W/m ² and using a battery of 444.445kW size	56
4.6	During Mode2, % deloading increased to ensure 0.444445MW reserve for frequency regulation	58
4.7	Units data	60
4.8	Transmission lines data	60
4.9	Load data	60
4.10	Bus load distribution profile	60
4.11	Comparison of cost in all the three cases	65
6.1	Ramp rate limit in various countries	79
6.2	Reference power and rotor status for different instants	87

LIST OF SYMBOLS

ρ	: Air density in Kg/m ³
β	: Pitch angle
λ	: Tip speed ratio
δ	: Voltage angle
ω	: Rotor speed
Δf	: Frequency deviation
$\Delta\omega$: Change in rotor speed
ΔV	: Voltage variation across a line
$\Delta V_{reserve}$: Shift in voltage due to deloading which is a measure of reserve available
η	: Power efficiency
A	: Ideality factor
A_b	: Area swept by the blade
a_v	: Temperature correction factor for voltage
C	: Capital Cost of unit in \$/kW
C_p	: Power coefficient
E_{es}	: Energy stored in the storage unit
f	: Frequency
H	: Inertia constant
i_d, i_q	: Direct and Quadrature axis components of current
i_{dref}	: Reference current corresponding to quadrature axis
I	: Installed capacity in kW
I_{ph}	: Short circuit current of a single string of PV array
I_{rs}	: Reverse saturation current of the diode
I_{SC}	: Cell's short circuit current at reference temperature and irradiation level
J	: Inertia of rotating mass
k	: Boltzmann's constant

K	: Kinetic energy
K_T	: Temperature coefficient of cell
K_i	: Integral gain of PI controller
K_p	: Proportional gain of PI controller
n_p	: Number of cells in parallel
n_s	: Number of cells in series
N	: Number of times battery replacement done during life of PV
O	: Operating Cost of unit in \$/kW
P	: Real power
P_{Di}^t	: Power demand at i^{th} bus at time t
P_{es}	Power delivered by energy storage unit
P_{gas}	: Power delivered by gas turbine
P_{gi}^t	: Power generation of i^{th} generator at time t
P_{gi}^{max}	: Maximum limit of Power generation of i^{th} generator
P_{gi}^{min}	: Minimum limit of Power generation of i^{th} generator
P_{ij}^t	: Power flow between bus i and j at time t
P_{total}	: Total power at PCC
P_{turbine}	: Power captured by wind turbine
P_{wind}	: Power from wind farm
q	: electron charge, $1.602 \times 10^{-19} \text{C}$
Q	: Reactive power
R	: Resistance of the line
R_r	: Ramp rate in pu/s
RD_{es}	Ramp down by energy storage unit
RD_i	: Ramp down of power at bus i
RU_i	: Ramp up of power at bus i
RU_{es}	: Ramp up by energy storage unit
S	: Irradiation in (W/m^2)
S_n	: Nominal apparent power
S_v	: Salvage of unit in \$/kW

SU_i	: Start-up cost of generator i
SD_i	: Shut-down cost of generator i
T	: Temperature in Kelvin
T_P	: Time period of study or life of PV
T_{ref}	: Reference temperature of cell in Kelvin
T_{STC}	: Temperature at standard test condition
u_i^t	: Unit status (ON/OFF) of generator at time t
V	: Nominal voltage across a line
v	: Wind velocity
v_d, v_q	: Direct and Quadrature axis components of voltage
V_{dc}	: Output dc voltage
V_{ac}	: Ac bus voltage
V_{dcref}	: Reference dc voltage
V_{deload}	Voltage corresponding to deloaded value
V_{MPP}	: Voltage at maximum power point
V_{MPP0}	Voltage at maximum power point at standard test conditions
X	: Reactance of the line

LIST OF ABBREVIATIONS

AGC	Automatic Generation Control
AESO	: Alberta Electric System Operator
AGC	: Automatic Generation Control
APF	: Active Power Filter
ASOS	Automated Surface Observing System
BESS	: Battery Energy Storage System
CERC	: Central Electricity Regulatory Commission
CAISO	: California Independent System Operator
DFIG	: Doubly Fed Induction Generator
DG	: Distributed Generation
ERCOT	: Electric Reliability Council of Texas
ESS	: Energy Storage System
EU	: European Union
FRT	: Fault Ride Through
HVRT	: High Voltage Ride Through
IEA	International Energy Agency
IEGC	: Indian Electricity Grid code
LVRT	: Low Voltage Ride Through
MPPT	: Maximum Power Point Tracking
NREL	: National Renewable Energy Laboratory
NYISO	: New York Independent System Operator
OLTC	: Over Load Tap Changer
PCC	: Point of Common Coupling
PMSG	: Permanent Magnet Synchronous Generator
PV	: Photovoltaic
RES	: Renewable Energy Source
RET	: Renewable Energy Target
RMS	: Root Mean Square

RSC : Rotor Side Converter
SPP : Southwest Power Pool Electric Energy Network
STC : Standard Test Condition
TSO : Transmission System Operator
WCED : World Commission on Environment and Development
WPP : Wind Power producer
WTG : Wind Turbine Generator