

ENERGY STORAGE SOLUTIONS FOR BETTER INTEGRATION OF WIND POWER

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by

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Certificate

This is to certify that the thesis entitled " **Energy Storage Solutions for Better Integration of Wind Power**", being submitted by **Ms. Gayathri Nair. S**, for the award of the degree of **Doctor of Philosophy** is a record of the bonafide research work carried out by her in the Department of Electrical Engineering of the Indian Institute of Technology Delhi India. Ms. Gayathri Nair. S, has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge, has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

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"A comfort zone is a beautiful place, but nothing ever grows there"-Anonymous

'The three things that are most essential to achievement are common sense, hard work and stick-to-it-iv-ness.'- Thomas Edison

The above two sentences aptly elucidate my Ph.D. But this work is no-where complete without my sincere gratitude to the people who gave me the opportunity and support to complete a very fulfilling tenure of Ph.D.

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Date:

(Gayathri Nair S)

Abstract

The future of wind power depends on the preparedness of the power system to attain higher penetration of wind power. Reducing dependency on conventional fossil generators have spurred the growth of wind power. The technical impediments to this are primarily the impact of wind variability on system stability, frequency and voltage profiles to be exact. Voltage and frequency limits that the interconnecting generators, both synchronous and asynchronous, have to follow are becoming more and more stringent and at present the levels to be maintained are within $\pm 10\%$ of the nominal value. Underfrequency and overfrequency limitations are also specified for different time frames beyond which the protection devices function to trip the system. In addition to this there are specifications in the case of the system becoming islanded and how the interconnection maintains voltage and frequency limits. Steps taken to ensure that wind power is observable and controllable by the system operator is a step toward integrating more wind in the system. This permits increasing the reliability of the wind power and thus the capacity credit of a wind farm. Having a more controllable power source which can be made to give power as and when the demand arises is the need of the hour. Cost effective storage solutions with higher capacities and fast ramping capabilities plays a large role in preventing these eventualities.

Different configurations of WECS offer different technical challenges. DFIG based variable speed system models, which are currently the most popular, can be studied to understand the modelling, control and working of a WECS. Optimal tracking of wind power which is enabled due to variable speed operation, allows more power capture. Wind power is erratic in nature and at times the power system may not be capable to accept the power generated. The solutions till date have been to curtail wind, work the WECS at deloaded condition or shut them down. At times of no

wind there will be deficit of power and this requires backup generator to fulfil its commitment. These solutions prevent utilising the wind power potential to its fullest and involves operating quick responding costly generation to be always on standby as reserve. The role of storage systems in mitigating this variability of wind power needs deliberation. Storage systems can store the excess power or give power when in deficit and thus contribute to increasing the efficiency and utility of the WECS. Power smoothing, frequency regulation and low voltage ride through are some of the problems that can be tackled by using storage. The wind power with ESS behaves like the conventional sources that are able to give constant power and economic returns. In the event of higher wind integration replacing more and more conventional sources the storage can give inertial support to regulate frequency

With multitude of storage systems to choose from, the selection of energy storage to work with is a problem on its own. Every storage mechanism has its own characteristics of operation and life span. ESS which are able to respond in the manner compatible with WECS must be chosen. They must be suitably controlled to achieve the accurate tracking of wind power to ensure that they respond without delay. Devices which can respond to fast and frequent variations need not necessarily be efficient and may require reinforcements from time to time. This can lead to economic repercussions. So a compromise between characteristics may be arrived at by using a combination of ESS devices. In this case an optimally sized storage is equally important as the cost of energy storage should not over ride the benefits. The use of intelligent strategies to optimize the storage size has shown benefits in the life span of the storage.

This thesis focusses on modelling, controlling and sizing of energy storage systems to facilitate better integration of wind power. Choosing to work with DFIG based systems the different interconnections of this WECS is explored with and without ESS. Improvement in the system characteristics is observed with the help of ESS solutions. The development of accurate models of ESS and control topologies that ensure that

the ESS works towards achieving a dispatchable WECS is developed. Sizing methodologies that manipulate the ESS to work in accordance with their operational characteristics are also developed. Investigating the validity of the above discussed solutions to actual system case studies are done. The thesis reaches a conclusion that inclusion of ESS systems which are better controlled and sized can allow better integration of wind power.

सार

पवन ऊर्जा का भविष्य पवन ऊर्जा के उच्चतर प्रवेश प्राप्त करने के लिए बिजली व्यवस्था की तैयारी पर निर्भर करता है। पारंपरिक जीवाश्म जनरेटरों पर निर्भरता कम करने से पवन ऊर्जा की वृद्धि को बढ़ावा मिला है। इसके लिए तकनीकी बाधा मुख्य रूप से सिस्टम स्थिरता, आवृत्ति और वोल्टेज प्रोफाइल पर पवन परिवर्तनशीलता का प्रभाव सटीक होना है। वोल्टेज और आवृत्ति सीमा कि परस्पर जनरेटर, सिंक्रोनस और एसिंक्रोनस दोनों, पालन करने के लिए अधिक से अधिक कठोर और वर्तमान में स्तरों होते जा रहे हैं बनाए रखा जाना अंकित मूल्य के 10 % के भीतर हैं। अल्पसंख्यक और अधिकता सीमाएं भी अलग-अलग समय के लिए निर्दिष्ट होती हैं, जिसके अलावा सुरक्षा उपकरण सिस्टम की यात्रा के लिए कार्य करते हैं। इस के अतिरिक्त इसमें सिस्टम के मामले में विनिर्देश दिए गए हैं जो द्वीप के रूप में बनते हैं और कैसे एक दूसरे का संबंध वोल्टेज और आवृत्ति सीमा को बनाए रखता है। यह सुनिश्चित करने के लिए कदम उठाए गए हैं कि सिस्टम में पवन ऊर्जा को देखने योग्य और नियंत्रणीय है सिस्टम में अधिक हवा को एकीकृत करने की ओर एक कदम है यह पवन ऊर्जा की विश्वसनीयता बढ़ाने की अनुमति देता है और इस प्रकार पवन खेत की क्षमता का श्रेय। एक और अधिक चालानयोग्य शक्ति स्रोत होने के नाते जो मांग और आने पर शक्ति देने के लिए किया जा सकता है, उस समय की आवश्यकता होती है उच्च क्षमता और तेज रैम्पिंग क्षमताओं के साथ लागत प्रभावी भंडारण समाधान एक बड़ी भूमिका निभाता है इन घटनाओं को रोकने में

डब्ल्यूईसीएस के विभिन्न विन्यास विभिन्न तकनीकी चुनौतियों की पेशकश करते हैं डीएफआईजी आधारित चर गति प्रणाली मॉडल, जो कि वर्तमान में सबसे लोकप्रिय हैं, को डब्ल्यूईसीएस के मॉडलिंग, नियंत्रण और काम को समझने के लिए अध्ययन किया जा सकता है। चर गति के संचालन के कारण सक्षम पवन ऊर्जा की अधिकतम ट्रेकिंग, अधिक शक्ति कैपचर की अनुमति देता है। पवन ऊर्जा प्रकृति में अनियमित है और कभी-कभी बिजली व्यवस्था उत्पन्न होने वाली बिजली को स्वीकार करने में सक्षम नहीं हो सकती है। आज तक का समाधान हवा में कटौती करने के लिए किया गया है, डब्ल्यूसीएस को भ्रष्ट स्थिति में काम करना है या उन्हें बंद कर दिया गया है। कभी-कभार हवा में बिजली की कमी नहीं होती है और इसके लिए बैकअप जनरेटर को अपनी प्रतिबद्धता को पूरा करने की आवश्यकता होती है। ये समाधान पवन ऊर्जा क्षमता का पूर्ण उपयोग करने से रोकते हैं और इसमें जल्द से जल्द खर्चीली पीढ़ी का उत्तर देना आरक्षित के रूप में स्टैंडबाय पर होना चाहिए। पवन ऊर्जा की इस परिवर्तनशीलता को कम करने में भंडारण प्रणालियों की भूमिका के लिए विचार-विमर्श की आवश्यकता है भंडारण प्रणाली अतिरिक्त शक्ति को संग्रहित कर सकती है या घाटे में बिजली दे सकती है और इस तरह से डब्ल्यूईसीएस की दक्षता और उपयोगिता बढ़ाने में योगदान देता है। पावर चौरसाई, आवृत्ति विनियमन और कम वोल्टेज की सवारी के माध्यम से कुछ समस्याएं हैं जिन्हें भंडारण का उपयोग करके सामना किया जा सकता है। ईएसएस के साथ पवन ऊर्जा परंपरागत स्रोतों की तरह बर्ताव करती है जो निरंतर शक्ति और आर्थिक लाभ दे सकते हैं अधिक से अधिक परंपरागत स्रोतों की जगह उच्च हवा के एकीकरण की स्थिति में भंडारण आवृत्ति को विनियमित करने के लिए अनिवार्य समर्थन दे सकता है

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पवन ऊर्जा के बेहतर एकीकरण की सुविधा के लिए यह थीसिस ऊर्जा भंडारण प्रणालियों के मॉडलिंग, नियंत्रण और आकार बदलने पर केंद्रित है। डीएफआईजी आधारित सिस्टम के साथ काम करना चुनना इस डब्ल्यूईसीएस के विभिन्न इंटरकनेक्शन के साथ और ईएसएस के बिना पता लगाया गया है। सिस्टम विशेषताओं में सुधार ईएसएस समाधान की मदद से मनाया जाता है। ईएसएस और नियंत्रण टोपोलॉजी के सटीक मॉडलों का विकास जो यह सुनिश्चित करता है कि ईएसएस एक प्रेषणीय WECS प्राप्त करने की दिशा में काम करता है। अपने ऑपरेटिंग विशेषताओं के अनुसार कार्य करने के लिए ईएसएस को हेरफेर करने वाले तरीके भी विकसित होते हैं। वास्तविक प्रणाली मामले के अध्ययन के लिए उपर्युक्त समाधान की वैधता की जांच कर रहे हैं। थीसिस एक निष्कर्ष पर पहुंचता है कि बेहतर नियंत्रण और आकार वाले ईएसएस सिस्टम को शामिल करने से पवन ऊर्जा के बेहतर एकीकरण की अनुमति मिल सकती है। पावर चौरसाई, आवृत्ति विनियमन और कम वोल्टेज की सवारी के माध्यम से कुछ समस्याएं हैं जिन्हें भंडारण का उपयोग करके सामना किया जा सकता है। ईएसएस के साथ पवन ऊर्जा परंपरागत स्रोतों की तरह बर्ताव करती है जो निरंतर शक्ति और आर्थिक लाभ दे सकते हैं अधिक से अधिक परंपरागत स्रोतों की जगह उच्च हवा के एकीकरण की स्थिति में भंडारण आवृत्ति को विनियमित करने के लिए अनिवार्य समर्थन दे सकता है

चुनने के लिए कई भंडारण प्रणालियों के साथ, ऊर्जा भंडारण के साथ काम करने का चयन अपने आप पर एक समस्या है प्रत्येक भंडारण तंत्र के संचालन और जीवन काल की अपनी विशेषताओं है। ईएसएस जो WECS के साथ संगत तरीके से प्रतिक्रिया करने में सक्षम हैं, उन्हें चुना जाना चाहिए। वे उचित रूप से पवन ऊर्जा के सटीक ट्रेकिंग प्राप्त करने के लिए नियंत्रित होने चाहिए ताकि वे बिना देरी के जवाब दे सकें। तेजी से और अक्सर भिन्नताओं के लिए प्रतिक्रिया दे सकते हैं जो डिवाइस आवश्यक रूप से कुशल नहीं हैं और समय-समय पर सुदृढीकरण की आवश्यकता हो सकती है। इससे आर्थिक नतीजों का सामना हो सकता है इसलिए ईएसएस उपकरणों के संयोजन का उपयोग करके विशेषताओं के बीच एक समझौता किया जा सकता है। इस मामले में एक बेहतर आकार का भंडारण उतना ही महत्वपूर्ण है जितना ऊर्जा

भंडारण की लागत लाभों पर नहीं चलनी चाहिए। भंडारण के आकार को अनुकूलित करने के लिए बुद्धिमान रणनीतियों के उपयोग ने भंडारण के जीवन काल में लाभ दिखाए।

पवन ऊर्जा के बेहतर एकीकरण की सुविधा के लिए यह थीसिस ऊर्जा भंडारण प्रणालियों के मॉडलिंग, नियंत्रण और आकार बदलने पर केंद्रित है। डीएफआईजी आधारित सिस्टम के साथ काम करना चुनना इस डब्ल्यूईसीएस के विभिन्न इंटरकनेक्शन के साथ और ईएसएस के बिना पता लगाया गया है। सिस्टम विशेषताओं में सुधार ईएसएस समाधान की मदद से मनाया जाता है। ईएसएस और नियंत्रण टोपोलॉजी के सटीक मॉडलों का विकास जो यह सुनिश्चित करता है कि ईएसएस एक प्रेषणीय WECS प्राप्त करने की दिशा में काम करता है। अपने ऑपरेटिंग विशेषताओं के अनुसार कार्य करने के लिए ईएसएस को हेरफेर करने वाले तरीके भी विकसित होते हैं। वास्तविक प्रणाली मामले के अध्ययन के लिए उपर्युक्त समाधान की वैधता की जांच कर रहे हैं। थीसिस एक निष्कर्ष पर पहुंचता है कि बेहतर नियंत्रण और आकार वाले ईएसएस सिस्टम को शामिल करने से पवन ऊर्जा के बेहतर एकीकरण की अनुमति मिल सकती है।

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Nomenclature

ΔU	Input vector
ΔX	State vector
ω	Speed of the generator [p.u]
ω_{turbpu}	Speed of the turbine[p.u]
θ_{tw}	Shaft twist angle [p.u]
H_g	Generator inertia [s]
H_t	Turbine inertia [s]
k_p	Scaling factor for wind turbines
K_s	Shaft stiffness[p.u torque/rad]
P_e	Generator power [p.u]
P_{turbpu}	Turbine power[p.u]
T_e	Generator torque[p.u]
T_{mpu}	Mechanical torque[p.u]
V_{wbase}	Base wind speed
V_{wpu}	Wind speed [p.u]
A	Plant matrix
C	Output matrix
D	Feed forward matrix

B	Control matrix
f_{Δ}	Frequency deviation
f_{cutoff}	Cutoff frequency
k_{opt}	Aerodynamic constant for wind turbines
L_B	Battery life cycles
L_{FW}	Flywheel life cycles
$P_{ref-bat}$	Power reference of BESS
P_{ref-fw}	Power reference of FESS
$P_{turb_{opt}}$	Optimal power
V_{tip}	Tip speed
β	Pitch angle [degrees]
ΔP	change in power
$\Delta\omega$	change in speed
λ	Tip speed ratio
λ_{opt}	Optimal tip speed ratio
ω_r	IM rotor speed in p.u
ω_s	Synchronous speed
ω_{sl}	slip frequency
ω_s	Stator frequency in chapter 2
ω_{turb}	Turbine rotor speed[rad/s]

ϕ	Field flux of DC machine [<i>Wb</i>]
ϕ_{ag}	Air-gap flux of induction machines
ψ_{dr}, ψ_{qr}	Rotor d-axis and q-axis flux linkage
ψ_{ds}, ψ_{qs}	Stator d-axis and q-axis flux linkage
ρ	Air density [<i>kg/m³</i>]
τ_m	Instantaneous torque of DC machine
θ_r	Rotor voltage vector angle of DFIG
θ_s	Stator voltage vector angle of DFIG
θ_{sl}	Slip angle of DFIG
A	Swept area of the wind turbine blades [<i>m²</i>]
B_m	Viscous friction coefficient
C_P	Battery capacity
C_p	Coefficient of performance
$C_{p_{opt}}$	Optimal power coefficient
$\cos\phi_s$	Stator power factor of DFIG
e	Tracking error
E_A	Armature voltage of DC machine [Volts]
e_b	Back e.m.f of DC machine
e'_d	IM <i>d</i> axis voltage behind transient reactance
e'_q	IM <i>q</i> axis voltage behind transient reactance

E_{rating}	Energy rating
f	Supply frequency
f_0	Nominal frequency
f_{ref}	Grid frequency
I	Battery current
I_a	Armature current of DC machine [A]
I_r	Rotor current of DFIG
I_s	Stator current of DFIG
i_{ds}	IM stator d axis current
i_{qs}	IM stator q axis current
J_m	Inertia of DC machine
k	Peukert constant
k_1	Control parameter
k_2	Control parameter 2
k_b	Back e.m.f constant of DC machine
k_m	Motor torque constant [volts/(rad/s)]
L_m	Mutual inductance
L_r	Rotor inductance
L_s	Stator inductance
P	Active power

p	number of poles
P_d	Dispatch power
P_m	Mechanical power
P_o	IM power output
P_r	Rotor power
P_s	Stator power
P_w	Wind power
P_{ag}	Air gap power
P_{BESS}	Long term power reference
P_{cur}	Rotor copper loss in DFIG
P_{cus}	Stator copper loss in DFIG
P_{ess}	ESS power reference
P_{FESS}	Short term power reference
P_{rating}	Power rating
P_{ref}	Power reference
P_{turb}	Wind turbine power
Q	Reactive power
R	Turbine rotor radius
R_r	Rotor resistance of DFIG
R_s	Stator resistance of DFIG

R_{eq}	equivalent resistance of RSC
s	slip
S_{base}	Rated capacity
T	Linear integral controller gain
t	Time [s]
T_0	IM transient open-circuit time constant
T_e	Electromechanical torque
T_L	Load torque
T_m	Mechanical torque
U_{acmeas}	Measured stator voltage
U_{dc}	DC link Voltage
V	Quadratic Lyapunov function in Chapter 5
V	Supply voltage
V_r	Rotor voltage of DFIG
V_s	Stator voltage of DFIG
V_w	Wind speed [m/s]
v_{dr}, v_{qr}	Rotor d-axis and q-axis voltage
v_{ds}, v_{qs}	Stator d-axis and q-axis voltage
V_{tmeas}	Voltage at PCC
V_{tref}	Reference voltage

X	IM open-circuit reactance
X'	IM short circuit reactance
X_{eq}	equivalent inductance of RSC
X_{lr}	Rotor leakage reactance of DFIG
X_{ls}	Stator leakage reactance of DFIG
Z	Vector of time intervals

Acronyms

AC	Alternating current
AGC	Automatic generation control
ARMA	Auto regressive moving average
BESS	Battery energy storage system
CAES	Compressed air energy storage
CCT	Critical clearing time
CAISO	California Independent system operator corporation
DC	Direct current
DFIG	Doubly fed induction generators
DSL	DIgSILENT simulation language
ESS	Energy storage system
FESS	Flywheel energy storage system
FERC	Federal electricity regulatory council
FFT	Fast Fourier Transform
GSC	Grid side converter
HESS	Hybrid energy storage system
IG	Induction generator
IGBT	Insulated gate bipolar transistor
IM	Induction machine
ISO	Independent system operators
LA	Lead acid
LVRT	Low voltage ride through
MPPT	Maximum power point tracking
MPP	Maximum power point

MTDC	Multi terminal DC connection
NAS	Sodium sulphur batteries
NiCd	Nickel-cadmium
PCS	Power conversion systems
PCC	Point of common coupling
PE	Power electronic
PHES	Pumped hydro-electric storage
PI	Proportional Integral
PM	Permanent magnet
PMSM	Permanent magnet synchronous machine
PMDC	Permanent magnet DC machine
PSO	Particle swarm optimisation
PV	Photovoltaics
PWM	Pulse width modulation
RSC	rotor side converter
RTO	Regional transmission operators
SCIG	Squirrel cage induction machine
SG	Synchronous generators
SMES	Super conducting magnetic energy storage
SOC	State of charge
STATCOM	Static synchronous compensator
TACAS	Thermal and compressed air energy storage
UPS	Uninterrupted power supply
VRB	Vanadium redox flow battery
VRLA	Valve regulated lead acid
VSC	Voltage source converters
WECS	Wind energy conversion systems
WPP	Wind power plant

