

**DESIGN AND DEVELOPMENT OF PV-SMALL HYDRO  
HYBRID SYSTEMS WITH SYNCHRONISATION  
TO WEAK GRID**

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TO WEAK GRID**

*by*

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**Submitted**

**in fulfilment of the requirements of the degree of Doctor of Philosophy  
to the**



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# **CERTIFICATE**

It is certified that the thesis entitled “**Design and Development of PV-Small Hydro Hybrid Systems with Synchronization to Weak Grid**” being submitted by Mr. Sunil Kumar Pandey for award of the degree of Doctor of Philosophy in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

**Dated: February 21, 2022**

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Sunil Kumar Pandey

## ABSTRACT

This work presents the PV-BES-small hydro-wind hybrid system with synchronization to the weak grid, which operates in three mode like the grid synchronized mode, an islanded mode, and hydro generator mode. This system ensures reliable and uninterrupted power to the critical loads in rural, hilly, and coastal areas, where the grid is weak. The conventional grid tied solar inverters are shut down compulsorily at the outage of the grid due to safety concerns. The grid in the remote, hilly, and coastal areas are subjected to the grid voltage amplitude variations, grid voltage frequency variations, and frequent outage of the grid occurs. Thus, the electricity to the dedicated loads is ensured by diesel generators. The environmental and economic concerns of diesel generator set, its high cost installation, operation, diesel transport to remote locations, emissions cause climate change due to global warming and other environmental issues because of release of the high amount of carbon dioxide and other toxic gases, have led to think on cost effective and pollution free energy. Moreover, fossil fuels are exhaustible and depleting, resulting in increased costs. These problems are mitigated by integrating the various renewable energy resources, and the battery energy storage (BES) accompanied to the efficient, accurate, and fast control strategy. The PV array generator is incompetent to ensure continuous electricity, while the PV array generation is low due to low irradiance than the load requirement at the outage of the utility grid. The BES stores energy at surplus generation from the PV array generator, and discharges to meet the load requirement, while deficient generation from the PV array at an islanded mode of operation. Moreover, the PV-BES system is controlled to function at variable grid power mode and preset grid power mode to ensure efficient utilization of the resources. The BES capacity required is large, moreover, BES needs replacement and frequent maintenance, thus, increases the cost of the installation and decreases reliability, especially, in remote hilly areas. The self excited induction generator functions at single point of the saturation region of its magnetization characteristics is utilized to realize the hydro generator. The hydro generator accompanied to PV array generator feeds the load and charges the BES at the utility grid outage. This decreases the BES capacity requirement and BES loading. Wind power is abundant in coastal areas. The wind generator, realized from the permanent magnet synchronous generator is integrated at the DC link to reduce the dependency of the emergency load on the weak utility grid. The PV array generator, wind generator, BES, and hydro generator are integrated to efficiently utilize the available renewable

resources. This PV-BES-small hydro-wind system is synchronized to the utility grid for the exchange of powers. The utility grid tied mode control, an islanded mode control, and transition mode control algorithms are adopted for the reliable control of the PV-BES-small hydro-wind system. The PV-BES-small hydro-wind system is integrated to the utility grid near the local loads rather than using a long transmission line for providing power to the loads.

The increased concentration of the power converters in the residential load causes a serious power quality concern. The nonlinear load injects harmonics current to the utility grid, which leads to voltage distortion, causes mal-operation of appliances, increased losses, and reactive power burden on the distribution network. The fast and accurate control algorithms are utilized to mitigate these harmonics current in the utility network current.

This investigation is focused on the design, development, and implementation of various single phase and three phase configurations of PV-small hydro hybrid systems with synchronization to the utility grid. All the topologies are simulated in MATLAB/ Simulink environment and validated on a developed laboratory prototype. These topologies ensure electricity to dedicated load with distribution grid power quality concern. The simulated and test results are utilized to analyse the utility grid synchronized mode, an islanded mode, and transition mode functions of various implemented configurations. The PV-BES-small hydro hybrid system configurations are classified based on their type of battery connection, type of utility grid (single-phase or three-phase), number of power conversion stages (single-stage or two-stage), and the renewable energy sources used. In the case of two stage power conversion stages, the first stage, which is a boost converter extracts the maximum power from the renewable sources. The remaining functions of power injection to the utility grid, harmonics current compensation, reactive power compensation of the non-linear load besides feeding the load are performed by the second stage, which is a utility grid interactive VSC. The bidirectional converter charges/ discharges the BES. In single stage conversion, all the function is performed by the VSC in the utility grid tied mode except BES charging and discharging, which is controlled by buck-boost converter. Whereas, in an islanded mode of single stage conversion, the bidirectional converter also tracks the MPPT. The VSC regulates the PCC voltage in an islanded mode in both the two stage conversion and single stage conversion. The utility grid outage is common in rural, hilly, and coastal areas. Therefore, simple, accurate, autonomous, and intelligent control techniques for utility grid synchronized PV-BES-small hydro hybrid system, are developed such that the PV-small hydro-hybrid system is capable of operating

under outage and recovery of the utility grid and at the outage and restoration of power generation from the renewable sources to ensure reliable and uninterrupted power to the end users.

## सार

यह काम पीवी-बीईएस-छोटे हाइड्रो-विंड हाइब्रिड सिस्टम को कमजोर ग्रिड के साथ सिंक्रोनाइज़ेशन के साथ प्रस्तुत करता है, जो ग्रिड सिंक्रोनाइज़्ड मोड, एक आइलैंडेड मोड और हाइड्रो जनरेटर मोड जैसे तीन मोड में संचालित होता है। यह प्रणाली ग्रामीण, पहाड़ी और तटीय क्षेत्रों में महत्वपूर्ण भार के लिए विश्वसनीय और निर्बाध बिजली सुनिश्चित करती है, जहां ग्रिड कमजोर है। पारंपरिक ग्रिड से जुड़े सोलर इनवर्टर सुरक्षा कारणों से ग्रिड के बंद होने पर अनिवार्य रूप से बंद हो जाते हैं। दूरस्थ, पहाड़ी और तटीय क्षेत्रों में ग्रिड वोल्टेज आयाम भिन्नताओं, ग्रिड वोल्टेज आवृत्ति भिन्नताओं के अधीन होते हैं, और ग्रिड का बार-बार आउटेज होता है। इस प्रकार, डीजल जनरेटर द्वारा समर्पित भार की बिजली सुनिश्चित की जाती है। डीजल जनरेटर सेट की पर्यावरण और आर्थिक चिंताओं, इसकी उच्च लागत स्थापना, संचालन, दूरदराज के स्थानों में डीजल परिवहन, उत्सर्जन ग्लोबल वार्मिंग के कारण जलवायु परिवर्तन और अन्य पर्यावरणीय मुद्दों के कारण कार्बन डाइऑक्साइड और अन्य जहरीली गैसों की उच्च मात्रा की रिहाई के कारण, लागत प्रभावी और प्रदूषण मुक्त ऊर्जा पर विचार करने के लिए प्रेरित किया है। इसके अलावा, जीवाश्म ईंधन घट रहे हैं, जिसके परिणामस्वरूप लागत में वृद्धि हुई है। विभिन्न अक्षय ऊर्जा संसाधनों, और बैटरी ऊर्जा भंडारण (बीईएस) को कुशल, सटीक और तेज नियंत्रण रणनीति के साथ एकीकृत करके इन समस्याओं को कम किया जाता है। पीवी सरणी जनरेटर निरंतर बिजली सुनिश्चित करने के लिए अक्षम है, जबकि यूटिलिटी ग्रिड के आउटेज पर लोड आवश्यकता से कम विकिरण के कारण पीवी सरणी उत्पादन कम है। बीईएस पीवी सरणी जनरेटर से अधिशेष उत्पादन पर ऊर्जा संग्रहीत करता है, और लोड की आवश्यकता को पूरा करने के लिए निर्वहन करता है, जबकि पीवी सरणी से कम उत्पादन ऑपरेशन के एक पृथक मोड में होता है। इसके अलावा, पीवी-बीईएस प्रणाली को संसाधनों के कुशल उपयोग को सुनिश्चित करने के लिए परिवर्तनीय ग्रिड पावर मोड और प्रीसेट ग्रिड पावर मोड पर कार्य करने के लिए नियंत्रित किया जाता है।

आवश्यक बीईएस क्षमता बड़ी है, इसके अलावा, बीईएस को प्रतिस्थापन और लगातार रखरखाव की आवश्यकता है, इस प्रकार, स्थापना की लागत बढ़ जाती है और विश्वसनीयता कम हो जाती है, खासकर दूरदराज के पहाड़ी क्षेत्रों में। अपने चुंबकीयकरण विशेषताओं के संतृप्ति क्षेत्र के एक बिंदु पर स्व-उत्तेजित प्रेरण जनरेटर का उपयोग हाइड्रो जनरेटर का एहसास करने के लिए किया जाता है। पीवी सरणी जनरेटर के साथ हाइड्रो जनरेटर लोड को फीड करता है और उपयोगिता ग्रिड आउटेज पर बीईएस को चार्ज करता है। यह बीईएस क्षमता की आवश्यकता और बीईएस लोडिंग को कम करता है। तटीय क्षेत्रों में पवन ऊर्जा प्रचुर मात्रा में है। स्थायी चुंबक तुल्यकालिक जनरेटर से प्राप्त पवन जनरेटर को कमजोर उपयोगिता ग्रिड पर आपातकालीन भार की निर्भरता को कम करने के लिए डीसी लिंक पर एकीकृत किया गया है। उपलब्ध अक्षय संसाधनों का कुशलतापूर्वक उपयोग करने के लिए पीवी सरणी जनरेटर, पवन जनरेटर, बीईएस और हाइड्रो जनरेटर एकीकृत हैं। यह पीवी-बीईएस-छोटा हाइड्रो-विंड सिस्टम शक्तियों के आदान-प्रदान के लिए उपयोगिता

ग्रिड के साथ सिंक्रनाइज़ है। पीवी-बीईएस-छोटे हाइड्रो-विंड सिस्टम के विश्वसनीय नियंत्रण के लिए उपयोगिता ग्रिड एकीकृत मोड नियंत्रण, एक पृथक मोड नियंत्रण, और संक्रमण मोड नियंत्रण एल्गोरिदम को अपनाया जाता है। पीवी-बीईएस-छोटे हाइड्रो-विंड सिस्टम को लोड को बिजली प्रदान करने के लिए एक लंबी ट्रांसमिशन लाइन का उपयोग करने के बजाय स्थानीय भार के पास उपयोगिता ग्रिड में एकीकृत किया गया है।

आवासीय भार में पावर कन्वर्टर्स की बढ़ी हुई एकाग्रता बिजली की गुणवत्ता की गंभीर चिंता का कारण बनती है। नॉनलाइनियर लोड यूटिलिटी ग्रिड में हार्मोनिक्स करंट को इंजेक्ट करता है, जो वोल्टेज विरूपण की ओर जाता है, उपकरणों के खराब संचालन, नुकसान में वृद्धि, और वितरण नेटवर्क पर प्रतिक्रियाशील बिजली के बोझ का कारण बनता है। यूटिलिटी नेटवर्क करंट में इन मौजूदा हार्मोनिक्स को कम करने के लिए तेज और सटीक नियंत्रण एल्गोरिदम का उपयोग किया जाता है।

यह जांच यूटिलिटी ग्रिड के साथ सिंक्रोनाइजेशन के साथ पीवी-स्मॉल हाइड्रो हाइब्रिड सिस्टम के विभिन्न सिंगल फेज और थ्री फेज कॉन्फिगरेशन के डिजाइन, विकास और कार्यान्वयन पर केंद्रित है। सभी टोपोलॉजी MATLAB/सिमुलिक वातावरण में सिमुलेटेड हैं और एक विकसित प्रयोगशाला प्रोटोटाइप पर मान्य हैं। ये टोपोलॉजी वितरण ग्रिड बिजली गुणवत्ता चिंता के साथ समर्पित लोड के लिए बिजली सुनिश्चित करते हैं। सिमुलेटेड और परीक्षण के परिणामों का उपयोग यूटिलिटी ग्रिड सिंक्रोनाइज़्ड मोड, एक आईलैंडेड मोड और विभिन्न कार्यान्वित कॉन्फिगरेशन के ट्रांज़िशन मोड फ़ंक्शंस का विश्लेषण करने के लिए किया जाता है। पीवी-बीईएस-छोटे हाइड्रो हाइब्रिड सिस्टम कॉन्फिगरेशन को उनके प्रकार के बैटरी कनेक्शन, उपयोगिता ग्रिड के प्रकार (एकल-चरण या तीन-चरण), बिजली रूपांतरण चरणों की संख्या (एकल-चरण या दो-चरण) के आधार पर वर्गीकृत किया जाता है, और नवीकरणीय ऊर्जा स्रोतों का उपयोग किया जाता है। दो चरण बिजली रूपांतरण चरणों के मामले में, पहला चरण, जो एक बढ़ावा कनवर्टर है, अक्षय स्रोतों से अधिकतम शक्ति निकालता है। शेष कार्य, यूटिलिटी ग्रिड में बिजली इंजेक्शन, हार्मोनिक्स धारा मुआवजा, लोड को खिलाने के अलावा गैर-रेखीय लोड की प्रतिक्रियाशील बिजली क्षतिपूर्ति दूसरे चरण द्वारा की जाती है, जो एक उपयोगिता ग्रिड इंटरैक्टिव वीएससी है। द्विदिश कनवर्टर बीईएस को चार्ज/डिस्चार्ज करता है। सिंगल स्टेज कन्वर्जन में, बीईएस चार्जिंग और डिस्चार्जिंग को छोड़कर यूटिलिटी ग्रिड टाईड मोड में वीएससी द्वारा सभी कार्य किए जाते हैं, जिसे हिरन-बूस्ट कन्वर्टर द्वारा नियंत्रित किया जाता है। जबकि, एकल चरण रूपांतरण के एक द्विपीय मोड में, द्विदिश कनवर्टर एमपीपीटी को भी ट्रैक करता है। वीएससी पीसीसी वोल्टेज को दो चरण रूपांतरण और एकल चरण रूपांतरण दोनों में एक पृथक मोड में नियंत्रित करता है। यूटिलिटी ग्रिड आउटेज ग्रामीण, पहाड़ी और तटीय क्षेत्रों में आम है। इसलिए, यूटिलिटी ग्रिड सिंक्रोनाइज़्ड पीवी-बीईएस-स्मॉल हाइड्रो हाइब्रिड सिस्टम के लिए सरल, सटीक, स्वायत्त और बुद्धिमान नियंत्रण तकनीकों को इस तरह विकसित किया गया है कि पीवी-स्मॉल हाइड्रो-हाइब्रिड सिस्टम आउटेज और यूटिलिटी ग्रिड की

रिक्वरी के तहत काम करने में सक्षम है। अंतिम उपयोगकर्ताओं को विश्वसनीय और अबाधित बिजली सुनिश्चित करने के लिए अक्षय स्रोतों से बिजली उत्पादन की कमी और बहाली पर।

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## LIST OF ABBREVIATIONS

DES	Distributed Energy Sources
PV	Photo Voltaic
BES	Battery Energy Storage
MPPT	Maximum Power Point Technique
P & O	Perturb & Observe
IC	Incremental Conductance
DC	Direct Current
AC	Alternating Current
PCC	Point of Common Coupling
DSTATCOM	Distribution Static Compensator
IGBT	Insulated Gate Bipolar Transistor
PQ	Power Quality
VSC	Voltage Source Converter
PLL	Phase Locked Loop
STS	Solid State transfer switch
DSP	Digital Signal Processor
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
PI	Proportional Integral
PVFF	PV Feed-Forward
UPS	Uninterrupted Power Supply
LED	Light Emitting Diode
CSI	Current Source Inverter
VSI	Voltage Source Inverter
PMBLDG	Permanent Magnet Brushless DC Generator
MG	Microgrid
PV-BES	Photovoltaic-Battery Energy Storage
PMSG	Permanent Magnet Synchronous Generator
SOC	State of Charge
ROGI	Reduced Order Generalized Integrator
SCGI	Squirrel Cage Induction Generator
FLL	Frequency Locked Loop
BPF	Band Pass Filter
LCO	Limit cycle Oscillator
S&H	Sample and Hold
ZCD	Zero Cross Detection
HCC	Hysteresis Current Controller
ACF	Adaptive Complex filter
QSG	Quadrature Signal Generator
MFOF	Modified First Order Filter
LQR	Linear Quadratic Regulator
CFDBPF	Center Frequency Digital Bandpass Filter
PWM	Pulse Width Modulation

## LIST OF SYMBOLS

$P_{pv}$	PV array power
$I_{pv}$	PV array current
$V_{pv}$	PV array voltage
$V_{mpp}$	MPP voltage
$I_{mpp}$	MPP current
$P_{mpp}$	MPP power
$V_{OCA}$	PV Array Open circuit PV voltage
$I_{SCA}$	PV Array Short circuit current
$V_{DC}$	DC link voltage
$V_{DC}^*$	Reference DC link voltage
$V_{DCE}$	DC link voltage error
$C_{DC}$	DC link capacitor of VSC
$R_s, C_s$	Ripple Filter
$L_f$	Interfacing Inductor
$V_{vsc}$	VSC Voltage Rating
$I_{vsca}$	VSC fundamental frequency active current component
$I_{vsr}$	VSC reactive component of current
$L_b$	Boost Converter Inductor
$D$	Boost Converter Duty Ratio
$f_s$	Boost Converter Switching Frequency
$i_s$	Utility Grid current
$v_s$	Utility Grid Voltage
$v_{s\alpha}, v_{s\beta}$	In phase and orthogonal PCC voltages
$u_\alpha, u_\beta$	In phase and Orthogonal unit templates
$i_{ref}$	Reference Utility Grid current
$i_{Lp}, i_{Lq}$	Load Current Orthogonal Component
$I_{pvff}$	PV Feed Forward Term
$I_b$	Battery Current
$I_b^*$	Estimated Battery Current
$I_{be}$	Error in Battery Current
$L_{bc}$	Bidirectional Converter Inductor
$v_{pcc}$	PCC Voltage
$V_p$	Amplitude of PCC Voltage
$i_{sa}, i_{sb}, i_{sc}$	Sensed Grid Current
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Estimated Reference Grid Currents
$i_{sab}, i_{sbc}$	Grid Line Current
$v_{sab}, v_{sbc}$	PCC Line Voltage
$v_{sa}, v_{sb}, v_{sc}$	Grid Phase Voltage
$V_t$	PCC Voltage Amplitude
$i_h$	Hydro Generator Current
$i_L$	Load Current
$V_w$	Wind Generator Voltage
$I_w$	Wind Generator Current