

ANALYSIS, DESIGN AND CONTROL OF SOLAR PV- SYSTEM WITH BATTERY FOR IMPROVED UTILIZATION OF DIESEL GENERATOR SET

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PV- SYSTEM WITH BATTERY FOR IMPROVED
UTILIZATION OF DIESEL GENERATOR SET**

by

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CERTIFICATE

It is certified that the thesis entitled “**Analysis, Design and Control of Solar PV- System with Battery for Improved Utilization of Diesel Generator Set,**” being submitted by **Mr. Gopal Krishan Taneja** for an award of the degree of **Doctor of Philosophy** in the Department of Energy Science and Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for any other degree or diploma award.

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Gopal Krishan Taneja

ABSTRACT

Solar photovoltaic (SPV)-battery microgrids in an islanded mode offer versatile solutions for decentralized energy generation. The diesel generator (DG) set based standalone supply systems are also source of electricity in many parts of world. DG sets are backbone of supply in remote areas, hospitals, institutes, telecommunication towers etc. However, 24 hours DG set operation increases overall cost of electricity and pollutes environment, diminishing main purpose of renewable energy-based microgrids. Moreover, a DG set is usually manufactured to work at a 0.8 lagging power factor to cater to the load reactive power demand. However, its power factor reaches around 0.5-0.6 in existing SPV-DG set-based microgrid due to sharing the load real power demand between the DG set and SPV system (SPVS). However, due to the unity power factor (UPF) operation of SPVS, the load reactive power burden is fed by the DG set alone. Hence, power factor of the DG set is considerably decreased, especially during the peak solar isolation situation, which reduces fuel efficiency and raises the overall energy cost. Moreover, nowadays many of such loads use power converters and some of them are nonlinear loads. Such loads draw harmonics currents, negative sequence currents and they result in voltage distortion, increased losses, increased fuel consumption and derating of DG sets. Therefore, this work focuses on the power quality improvement of the DG set based standalone supply systems with solar photovoltaic (SPV) array with and without a battery energy storage (BES) integration.

This work deals with boosting the DG set's utilization by using SPVS power converter available capacity as the distribution static compensator (DSTATCOM). Key highlights of this work are as follows.

- DG set power factor is regulated at unity irrespective of SPV system generation with and without BES or load behaviour, enhancing the efficiency of the diesel engine and electric generator. Hence, the fuel consumption is decreased, lowering the cost of electricity.
- SPV system carries entire burden of the load's reactive power. Hence, the DG set's surplus capacity, which is initially reserved for the load reactive power, is used to commit the additional load on the same rating system.
- Since SPV system utilization factor is raised due to its 24 hours operation, its payback period is less than the existing system.

- The operation of SPV system with and without BES elevates power quality performance of DG set based microgrid without causing any high additional cost to the system. Thus, the IEEE std. 519 is followed at POI, with improved utilization of the microgrid.

Most commonly used machine in DG sets is wound rotor type synchronous generator with automatic voltage regulator. The frequency of supply is controlled by speed regulation of a diesel engine through governor mechanism and load leveling. However, the voltage is controlled using AVR (Automatic Voltage Regulator) with SPV-BES. SPV-BES based DG set based microgrid is used to control the terminal voltage, harmonics elimination, reactive power compensation, power factor correction and load balancing. A battery energy storage (BES) with SPV array is also used to improve fuel efficiency of the diesel engine. SPV array and battery on DC link of VSC (Voltage Source Converter) of this system are used to supply the active power to loads and it stores the energy during light load periods so that the DG set is always loaded with an optimum load of 80% to 100% of the generator rating. An optimum loading of DG set helps in improving the fuel efficiency of the diesel engine. BES also mitigates fluctuations in real power demand of loads. The use of BES helps in better voltage and frequency regulation of the system. Performance of DG systems is tested under steady state and dynamic conditions for linear and nonlinear loads.

Reference source currents are generated using an adaptive algorithm based on least mean $2L_{th}$ (LM2L) to filter nonlinear load currents to investigate performance of single-stage SPV-DG set based microgrids. Performance of adaptive LM2L filter algorithm is compared with N-LMS and N-LMS filters, and it has been demonstrated that LM2L adaptive algorithm has a better steady state and dynamic responses. Moreover, in a two-stage solar PV-DG set based microgrid, an improved variable step normalized adaptive filter (IVS-NAF) control algorithm is used for enhancing power quality of a standalone microgrid. The cascaded generalized second-order integrator (C-SOGI) based phase-locked loop (PLL) is used in single stage solar photovoltaic-BES-DG set based microgrid to improve power quality of this system. Finally, a generalized maximum correntropy criteria (GMCC) adaptive filter based control approach is used to improve power quality in a double stage solar photovoltaic-BES-DG set based microgrid under varying loads and solar PV generation.

सार

आइलैंडेड मोड में संचालित सौर फोटोवोल्टिक (SPV)-बैटरी माइक्रोग्रिड, विकेन्द्रीकृत ऊर्जा उत्पादन के लिए बहुपयोगी समाधान प्रदान करते हैं। डीज़ल जनरेटर (DG) सेट आधारित स्टैंडअलोन सप्लाय सिस्टम भी विश्व के कई हिस्सों में बिजली के स्रोत के रूप में उपयोग में लिए जाते हैं। DG सेट दूरस्थ क्षेत्रों, अस्पतालों, संस्थानों, दूरसंचार टावरों आदि में आपूर्ति की रीढ़ माने जाते हैं। किंतु, DG सेट का 24 घंटे संचालन बिजली की कुल लागत बढ़ा देता है और पर्यावरण को प्रदूषित करता है, जिससे नवीकरणीय ऊर्जा आधारित माइक्रोग्रिड का मुख्य उद्देश्य प्रभावित होता है। इसके अलावा, DG सेट सामान्यतः 0.8 लैगिंग पावर फैक्टर पर कार्य करने हेतु निर्मित होते हैं ताकि लोड की रिएक्टिव पावर माँग को पूरा किया जा सके। किंतु, मौजूदा SPV-DG सेट आधारित माइक्रोग्रिड में DG सेट का पावर फैक्टर लगभग 0.5-0.6 तक गिर जाता है क्योंकि लोड की वास्तविक पावर माँग DG सेट और SPV सिस्टम (SPVS) के बीच साझा होती है। चूँकि SPVS यूनिटी पावर फैक्टर (UPF) पर संचालित होता है, अतः लोड की रिएक्टिव पावर की पूरी पूर्ति DG सेट द्वारा ही की जाती है। इसलिए, DG सेट का पावर फैक्टर विशेष रूप से अधिक सौर विकिरण की स्थिति में काफी घट जाता है, जिससे ईंधन दक्षता कम होती है और कुल ऊर्जा लागत बढ़ती है। इसके अतिरिक्त, वर्तमान समय में ऐसे कई लोड पावर कन्वर्टर्स का उपयोग करते हैं और उनमें से कुछ नॉन-लिनियर लोड होते हैं। ऐसे लोड हार्मोनिक करंट, निगेटिव सीकेंस करंट खींचते हैं और परिणामस्वरूप वोल्टेज डिस्टॉर्शन, अधिक हानियाँ, अधिक ईंधन खपत और DG सेट की डीरेटिंग होती है। इसलिए, यह शोध कार्य DG सेट आधारित स्टैंडअलोन सप्लाय सिस्टम की पावर क्वालिटी सुधार पर केंद्रित है, जिसमें सौर फोटोवोल्टिक (SPV) एरे बैटरी एनर्जी स्टोरेज (BES) के साथ और बिना एकीकृत किया गया है।

यह शोध कार्य SPVS पावर कन्वर्टर की उपलब्ध क्षमता का उपयोग डिस्ट्रीब्यूशन स्टैटिक कम्पेन्सेटर (DSTATCOM) के रूप में करके DG सेट के उपयोग को बढ़ाने पर आधारित है। इस शोध के प्रमुख बिंदु निम्नलिखित हैं: • DG सेट का पावर फैक्टर यूनिटी पर नियंत्रित रहता है, चाहे SPV सिस्टम की जनरेशन और BES या लोड का व्यवहार कुछ भी हो, जिससे डीज़ल इंजन और इलेक्ट्रिक जनरेटर की दक्षता बढ़ती है। परिणामस्वरूप ईंधन की खपत कम होती है और बिजली की लागत घटती है। • SPV सिस्टम लोड की पूरी रिएक्टिव पावर का वहन करता है। अतः DG सेट की अतिरिक्त क्षमता, जो प्रारंभ में लोड की रिएक्टिव पावर के लिए आरक्षित होती थी, अब उसी रेटिंग सिस्टम पर अतिरिक्त लोड संभालने में प्रयोग होती है। • SPV सिस्टम का उपयोग फैक्टर 24 घंटे संचालन के कारण बढ़ता है, जिससे इसकी पेबैक अवधि मौजूदा सिस्टम की तुलना में कम होती है। • BES के साथ और बिना SPV सिस्टम का संचालन DG सेट आधारित माइक्रोग्रिड की पावर क्वालिटी को बिना किसी बड़ी अतिरिक्त लागत के बेहतर बनाता है। परिणामस्वरूप, IEEE मानक 519 का पालन पॉइंट ऑफ इंटरकनेक्शन (POI) पर किया जाता है और माइक्रोग्रिड का उपयोग बेहतर होता है।

DG सेट में सर्वाधिक प्रचलित मशीन वाउंड रोटर प्रकार की सिंक्रोनस जनरेटर होती है जिसमें ऑटोमैटिक वोल्टेज रेगुलेटर (AVR) लगा होता है। सप्लाय की आवृत्ति डीज़ल इंजन की स्पीड को गवर्नर मैकेनिज्म और लोड लेवलिंग द्वारा नियंत्रित करके तय की जाती है। जबकि वोल्टेज को SPV-BES के साथ AVR द्वारा नियंत्रित किया जाता है। SPV-BES आधारित DG सेट माइक्रोग्रिड का उपयोग टर्मिनल वोल्टेज नियंत्रण, हार्मोनिक्स उन्मूलन, रिएक्टिव पावर क्षतिपूर्ति, पावर फैक्टर सुधार और लोड बैलेंसिंग के लिए किया जाता है। SPV एरे के साथ बैटरी एनर्जी स्टोरेज (BES) डीज़ल इंजन की ईंधन दक्षता में सुधार के लिए भी प्रयोग होता है। इस सिस्टम के VSC (वोल्टेज सोर्स कन्वर्टर) के DC लिंक पर स्थित SPV एरे और बैटरी का उपयोग लोड को सक्रिय पावर देने और हल्के लोड के समय ऊर्जा संग्रहित करने के लिए किया जाता है ताकि DG सेट हमेशा जनरेटर रेटिंग के 80% से 100% तक के आदर्श लोड पर कार्य करे। DG सेट का आदर्श लोडिंग डीज़ल इंजन की ईंधन दक्षता में सुधार करती है। BES लोड की वास्तविक

पावर माँग में उतार-चढ़ाव को भी नियंत्रित करता है। BES के प्रयोग से सिस्टम की वोल्टेज और आवृत्ति नियंत्रण क्षमता बेहतर होती है। DG सिस्टम का प्रदर्शन रैखिक और गैर-रैखिक लोड के लिए स्थिर अवस्था और गतिशील अवस्था में परखा गया है।

संदर्भ स्रोत करंट्स एक एडेप्टिव एल्गोरिद्म (least mean 2Lth - LM2L) द्वारा उत्पन्न किए जाते हैं, जो नॉन-लिनियर लोड करंट्स को फ़िल्टर करने और सिंगल-स्टेज SPV-DG सेट आधारित माइक्रोग्रिड के प्रदर्शन की जांच करने के लिए उपयोग किया गया है। LM2L फ़िल्टर एल्गोरिद्म के प्रदर्शन की तुलना N-LMS और N-LMS फ़िल्टर्स से की गई है, और यह प्रदर्शित किया गया है कि LM2L एडेप्टिव एल्गोरिद्म का स्थिर और गतिशील दोनों प्रतिक्रियाओं में बेहतर प्रदर्शन है। इसके अलावा, दो-स्टेज सोलर PV-DG सेट आधारित माइक्रोग्रिड में, एक उन्नत वेरिएबल स्टेप नॉर्मलाइज़्ड एडेप्टिव फ़िल्टर (IVS-NAF) कंट्रोल एल्गोरिद्म का उपयोग स्टैंडअलोन माइक्रोग्रिड की पावर क्वालिटी को बढ़ाने के लिए किया गया है। एकल-स्टेज सोलर फोटोवोल्टिक-BES-DG सेट आधारित माइक्रोग्रिड में पावर क्वालिटी सुधार हेतु कैस्केडेड जनरलाइज़्ड सेकंड-ऑर्डर इंटीग्रेटर (C-SOGI) आधारित फेज-लॉकड लूप (PLL) का प्रयोग किया गया है। अंततः, दोहरे चरण के सोलर फोटोवोल्टिक-BES-DG सेट आधारित माइक्रोग्रिड में, परिवर्तित लोड और सौर PV जनरेशन की स्थिति में पावर क्वालिटी सुधारने हेतु जनरलाइज़्ड मैक्सिमम कोरेंट्रॉपी क्राइटेरिया (GMCC) एडेप्टिव फ़िल्टर आधारित नियंत्रण दृष्टिकोण का उपयोग किया गया है।

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LIST OF ABBREVIATIONS AND VARIABLES

BES	Battery Energy Storage.
DG	Diesel Generator.
IVS	Improved Variable Step.
LMS	Least Mean Square.
MG	Microgrid.
MPPT	Maximum Power Point Tracking.
NAF	Normalized Adaptive Filter.
PCC	Point of Common Coupling.
RES	Renewable Energy Sources
SM	Synchronous Machine
SPVP	Solar Photovoltaic Plant.
THD	Total Harmonic Distortion.
UPF	Unity Power Factor.
VSC	Voltage Source Converter.
C_{dc}	DC Link Capacitor.
D	Boost Converter Switching Pulse.
L_B, L_v	SPVP Boost Converter and VSC Inductors.
u_{DG}	DG Set Unit Templates.
V_{t_ph}	DG Set Phase Voltage Peak Amplitude.
V_{MPP}, V_{PV}, I_{PV}	PV Reference and Sensed Voltage, Current.
V_{dc}^*, V_{dc}	Reference and Sensed DC Link Voltage.
V_f	DG Set Excitor Voltage.
v_{DG}, i_{DG}	DG Set Voltages and Currents.
i_{DG}^*	Reference DG Set Currents.
i_{vsc}	SPVP Inverter/ VSC Currents.
v_L, i_L	Sensed Load Voltages and Currents.
I_{DG}^*, I_{DG}	Reference and Estimated Active Component Amplitude of i_{DG}^* .
I_{Loss}	Loss Component Current Amplitude.
I_{PVFF}	PV Feed-Forward Component.
I_L, I_{L1}	Sensed and Filtered Fundamental Load Current Amplitudes.
P_{DG}, P_L, P_{PV}	DG, Load, SPVP Powers.
α	Step Size of IVS-NAF.
β	Internal Control Variable.
γ	Positive Variable Regularization Factor.
δ	Null Error Restraining Variable.
k	Constant Parameter.
σ	Variance Statistical Operator.
E	Expectation Statistical Operator.
DSTATCOM	Distribution static compensator.
N-LMF	Normalized least mean fourth.
N-LMS	Normalized least mean square.
PF	Power factor.
POI	Point of interconnection

SPV	Solar photovoltaic.
SPVP	Solar photovoltaic plant.
$i_{DGa}, i_{DGb}, i_{DGc}$	DG line currents.
i_{La}, i_{Lb}, i_{Lc}	Load line currents.
$i_{SPVPa}, i_{SPVPb}, i_{SPVPc}$	SPVP or VSC line currents.
I_{pv}, V_{pv}, P_{pv}	PV array current, voltage, and power.
V_{dc}	VSC's DC link voltage.
v_{DGab}, v_{DGbc}	Sensed line voltages of DG set.
$v_{DGa}, v_{DGb}, v_{DGc}$	Estimated phase voltages of DG set.
$u_{DGa}, u_{DGb}, u_{DGc}$	Unit template vectors.
P_{DG}, Q_{DG}	Active and reactive powers of DG set.
P_L, Q_L	Active and reactive powers of load.
P_{SPVP}, Q_{SPVP}	Active and reactive powers of SPVP.
$w_{pLa}, w_{pLb}, w_{pLc}$	Load current active fundamental components amplitude.
μ, λ, δ	Constants of LM2L algorithm.