POWER QUALITY IMPROVEMENT AND ENERGY MANAGEMENT OF VFD BASED AIR CONDITIONING SYSTEM USING PHOTOVOLTAIC WITH BATTERY STORAGE

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DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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CERTIFICATE

This is to certify that the dissertation entitled '**Power Quality Improvement and Energy Management of VFD Based Air Conditioning System Using Photovoltaic with Battery Storage**', being submitted by **Mr. Dhiman Das** 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 at Indian Institute of Technology Delhi, New Delhi.

Mr. Dhiman Das has worked under our supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

In tropical countries, air conditioning system consumes a significant amount of power ($\approx 1.5 - 3$ kW) from the utility grid and such loads create stress on the grid during peak hours. Photovoltaic (PV) power generation and air conditioning load are directly co-related. Recently with rapid development of power electronics, air conditioners are migrated to operate at variable speeds using variable frequency drive (VFD) technology. In this research work, PV generation and battery energy storage (BES) are integrated to air conditioning system so that the power consumption from the utility grid is reduced. BES compensates the effect of intermittency in the PV generation due to the environmental changes. Considering the advantage of VFD technology, the PV array and battery power is directly injected into the DC bus of VFD using a DC-DC converter without interrupting the main operation of the air conditioner. Due to the high frequency DC-DC conversion, high power DC-AC (50 Hz) conversion stage is eliminated, and seamless power is exchanged between the BES, PV generation and the utility grid. Thus, bulkiness of the system, cost and conversion losses are reduced as well as efficiency and reliability of the system are enhanced. Moreover, the air conditioner system can be operated uninterruptedly even in case of grid failure. As the price of PV panel is getting cheaper day by day, therefore, the one time installation cost of the system is to be compensated with energy bill paid by the user over long duration of time.

As the VFD consists of power electronics switches and diode bridge rectifier (DBR), therefore, the grid current becomes distorted during the operation. As a result, total harmonics distortion (THD) and 3rd harmonic component of the grid current are increased, which creates an adverse impact on the distribution transformer and low voltage power line. In this research work, the power quality (PQ) issues of the air conditioning system are mitigated using power factor corrector (PFC) converter as well as the power consumption from the grid is reduced by integrating the PV power and battery energy storage (BES). Furthermore, the PV generation is used to support the load as well as excess generation is fed back to the grid. A voltage source converter (VSC) is interfaced at the input stage of VFD, which is controlled to feed power to the grid as well as to improve the waveshape of the input grid current. The PV and BES power is directly injected into the DC bus of VFD by boosting the voltage level of the BES using a dual active bridge (DAB) converter.

A seamless power is exchanged in a bidirectional way between the utility grid and BES with improved PQ.

A small-scale laboratory prototype of the system is set up for the validation of the concept. The effect of injecting power at the DC bus of VFD is investigated with different scenarios. Under all test conditions, the THD of the grid current is found within the limits of the IEC 6100-3-2 standard.

सार

उष्णकटिबंधीय देशों में, एयर कंडीशनिंग सिस्टम उपयोगिता ग्रिड से महत्वपूर्ण मात्रा में बिजली (1.5-3 kW) की खपत करता है और इस तरह के भार पीक आवर्स के दौरान ग्रिड पर तनाव पैदा करते हैं। फोटोवोल्टिक बिजली उत्पादन और एयर कंडीशनिंग लोड सीधे सह-संबंधित हैं। हाल ही में पावर इलेक्ट्रॉनिक्स के तेजी से विकास के साथ, एयर कंडीशनर को वेरिएबल फ्रीक्वेंसी ड्राइव तकनीक का उपयोग करके परिवर्तनशील गति से संचालित करने के लिए स्थानांतरित किया गया है। इस शोध कार्य में, पीवी पावर और बैटरी एनर्जी स्टोरेज को एयर कंडीशनिंग सिस्टम में एकीकृत किया गया है ताकि यूटिलिटी ग्रिड से बिजली की खपत कम हो। बैटरी, पर्यावरणीय परिवर्तनों के कारण पीवी पीढ़ी में आंतरायिकता के प्रभाव की भरपाई करती है। वीएफडी तकनीक के लाभ को ध्यान में रखते हुए, एयर कंडीशनर के मुख्य संचालन को बाधित किए बिना डीसी-डीसी कनवर्टर का उपयोग करके सौर ऊर्जा और बैटरी पावर को सीधे वीएफडी की डीसी बस में इंजेक्ट किया जाता है। उच्च आवृत्ति डीसी-डीसी रूपांतरण के कारण, उच्च शक्ति डीसी-एसी (50 हर्ट्ज) रूपांतरण चरण समाप्त हो गया है, और बैटरी, सौर उत्पादन और उपयोगिता ग्रिड के बीच निर्बाध बिजली का आदान-प्रदान किया जाता है। इस प्रकार, प्रणाली की भारीता, लागत और रूपांतरण हानियों को कम किया जाता है और साथ ही प्रणाली की दक्षता और विश्वसनीयता को बढ़ाया जाता है। इसके अलावा, ग्रिड की विफलता के मामले में भी एयर कंडीशनर सिस्टम को निर्बाध रूप से संचालित किया जा सकता है। चूंकि सौर पैनल की कीमत दिन-ब-दिन सस्ती होती जा रही है, इसलिए सिस्टम की एकमुश्त स्थापना लागत की भरपाई उपयोगकर्ता द्वारा लंबे समय तक भुगतान किए गए ऊर्जा बिल से की जानी है।

चूंकि वीएफडी में पावर इलेक्ट्रॉनिक्स स्विच और डायोड ब्रिज रेक्टिफायर होते हैं, इसलिए ऑपरेशन के दौरान ग्रिड करंट विकृत हो जाता है। इसलिए, ग्रिड करंट के टीएचडी और तीसरे हार्मोनिक घटक को बढ़ा दिया जाता है, जो वितरण ट्रांसफार्मर और कम वोल्टेज बिजली लाइन पर प्रतिकूल प्रभाव डालता है। इस शोध कार्य में, पावर फैक्टर करेक्टर कन्वर्टर का उपयोग करके एयर कंडीशनिंग सिस्टम की बिजली की गुणवत्ता के मुद्दों को कम किया जाता है और साथ ही पीवी पावर और बैटरी ऊर्जा भंडारण को एकीकृत करके ग्रिड से बिजली की खपत को कम किया जाता है। इसके अलावा, सौर उत्पादन का उपयोग भार को समर्थन देने के लिए किया जाता है और साथ ही अतिरिक्त उत्पादन को ग्रिड में वापस फीड किया जाता है। एक वोल्टेज स्रोत कनवर्टर वी के इनपुट चरण में इंटरफेस किया जाता है, जिसे ग्रिड को पावर फीड करने के साथ-साथ इनपुट ग्रिड करंट के वेवशेप में सुधार करने के लिए नियंत्रित किया जाता है। डीएबी कन्वर्टर का उपयोग करके बैटरी के वोल्टेज स्तर को बढ़ाकर सौर ऊर्जा और बैटरी पावर को सीधे वीएफडी की डीसी बस में इंजेक्ट किया जाता है। बेहतर बिजली की गुणवत्ता के साथ उपयोगिता ग्रिड और बैटरी के बीच एक निर्बाध बिजली का आदान-प्रदान द्विदिश तरीके से किया जाता है।

अवधारणा के सत्यापन के लिए प्रणाली का एक लघु-स्तरीय प्रयोगशाला प्रोटोटाइप स्थापित किया गया है। वीएफडी की डीसी बस में इंजेक्शन लगाने की शक्ति के प्रभाव की विभिन्न स्थितियों के साथ जांच की जाती है। सभी परीक्षण स्थितियों के तहत, ग्रिड करंट का टीएचडी IEC 6100-3-2 मानक की सीमा के भीतर पाया जाता है।

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LIST OF ABBREVIATIONS

AC	Alternating current
DC	Direct current
Ah	Ampere hour
kW	Kilo-watt
PQ	Power quality
PF	Power factor
PFC	Power factor corrector
THD	Total harmonic distortion
ZVS	Zero voltage switching
SOC	State of charge
G2V	Grid to vehicle
V2G	vehicle to grid
HV	High voltage
LV	Low voltage
CC	Constant current
CV	Constant voltage
PV	Photovoltaic
VSC	Voltage source converter
MOSFET	Metal oxide field effect transistors
DSP	Digital signal processor
FPGA	Field-programmable gate array
PWM	Pulse width modulation
DBR	Diode bridge rectifier
GaN	Gallium nitride
SiC	Silicon carbide
DAB	Dual active bridge
IC	Integrated circuit
OPAMP	Operational Amplifier
PSFB	Phase shifted full bridge
ADC	Analog to digital conversion
PI	Proportional integral
DSO	Digital storage oscilloscope

LIST OF SYMBOLS

I_{Grid}	Current drawn from the grid (A)
I_{COM}	Current drawn by the VFD (A)
$I_{COM_R}, I_{COM_Y}, I_{COM_B}$	Current drawn by the compressor in each phase (A)
P_{COM}	Consumed electrical power of the compressor unit (W)
Q_{COM}	Refrigerating capacity the compressor unit (W)
f_{COM}	Driving frequency set by the inverter (Hz)
τ_{COM}	time constant of the compressor
$k_P,\ k_Q,\ \mu_P,\ \mu_Q$	constant coefficients of the air conditioner
V_{AC}	Grid voltage (V)
V_O	the DC bus voltage of VFD (V)
V_{PV}	Voltage across the PV array (V)
I_{PV}	Current drawn from the PV array (A)
P_{PV}	Power drawn from the PV array (W)
I_O	Current injected from/to the DC bus of VFD (A)
I_{MPPT}	Output current of the MPPT converter (A)
I_{BATT}	Current flowing from/into the battery (A)
V_{BATT}	Voltage across the battery (V)
I_{PFC}	Current drawn from the PFC (A)
$I_{L_{PFC}}$	Current flowing from the inductor of PFC (A)
V_{Ref}	Voltage reference for the converter
I_{Ref}	Current reference for the converter
P_{Ref}	Power reference for the converter
V_M & I_M	Sensed voltage and current by the sensor
V_{Pri}	Voltage across the LV side of the transformer (V)
I_{Pri}	Current flowing through LV side of the transformer (A)
ϕ	Phase shift angle between the bridge voltages (rad)
D	Duty cycle of the converter ($\%$)
V_{MPP}	Voltage of the PV array at MPP (V)
V_{con}	Control voltage for the phase modulator (V)
G	Solar irradiation (W/m^2)
T_s	Time period of single switching cycle of the converter (μs)