DESIGN AND DEVELOPMENT OF A PHASE SYNCHRONOUS INVERTER FOR MICROGRID SYSTEM BASED ON ELECTROSTATIC GENERATOR

BY

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ABSTRACT

The demand for energy sources of the world is exponentially increasing, which is in turn giving rise to a threatening insufficiency of fossil fuels and gases to be used as energy sources. Beyond this traditional and momentary solution to the energy crisis, the renewable energy-driven electrostatic generators provide the scope of a long-term solution. However, the electrostatic generator (ESG) with renewable energy should convert to supply AC for microgrid, but an inversion of the high voltage static DC has suffered many problems, such as inferior quality of waveform, stabilization of the input voltage, high switching loss due to phase synchronize and power quality as well as high unexpected voltage. Furthermore, an electrostatic generator produces high voltage DC and low current which is milliamperes (mA). Therefore, to overcome those issues, a new zero-crossing based voltage source phase synchronous inverter (PSI) circuit has been proposed in the microgrid system, which especially makes the AC waveform, free from higher harmonic distortion, low switching loss, and increased efficiency. A zero-crossing pulse width signal is generated to precisely synchronize with a microgrid line frequency that is done by switching and logic networks. A zero-crossing circuit is utilized to detect the phase with frequency, to make a zero-crossing signal and synchronize the phase angle between inverter and microgrid system. In this study, the unique inverter switching parameters are optimized, such as input source voltage of 10kV_{DC}, the duty cycle of 95%, switching frequency 2kHz and a microgrid load of 1000Ω, whereas the other parameters are considered. In addition, an LCL lowpass filter is used to couple between inverter and microgrid system, to convert square wave to pure sinusoidal wave and to reduce the higher harmonic distortion. Both the new proposed design and existing design are simulated by MatLab16.a/Simulink, Or CAD Capture 16.6, Proteus 8 professional and Keysight BenchVue. From this analysis, without the filtering condition and with the filtering condition of total harmonic distortion (THD) is 47.9% to 2.1%, which is approximately a 45% reduction in the higher harmonic distortion. The phase analysis showed that the error of an inverter side phase angle and microgrid side phase angle are 26.34° and 2.54°, respectively. The theoretical, simulated and experimental results have shown that the newly designed inverter has performed better in terms of the overall system conversion efficiency of 96.6%, the phase angle of 2.54°, and THD of about 2.1%. The proposed PSI is appropriate for microgrid applications that could contribute to the economic improvement of the country and globally as a whole.

خلاصة البحث

يزداد الطلب على مصادر الطاقة في العالم بشكل كبير ، وهذا بدوره يؤدّي إلى التهديد بعدم كفاية الوقود الأحفوري والغاز الطبيعي لاستخدامهما كمصادر للطاقة. وبالإضافة إلى الحلول التقليدية والسريعة لأزمة الطاقة، توفر المولدات الكهروستاتيكية التي تعتمد على الطاقة المتجددة حلاً طويل الأجل. ومع ذلك، يجب أن يتم تحويل مولد الطاقة الكهروستاتيكية (ESG) مع الطاقة المتجددة لتوفير التيار المتردد من أجل الشبكة الكهربائية الدقيقة، ولكن انعكاس التيار الثابت DC عانى الكثير من المشاكل، منها الجودة المتدنية للشكل الموجي ، استقرار الجهد المدخل، ارتفاع فقدان التحويل بسبب تزامن المرحلة ونوعية الطاقة وكذلك الجهد العال غير المتوقع. علاوة على ذلك، ينتج المولد الإلكتروستاتي جهداً عالياً للتيار الثابت DC وتياراً منخفضاً بقمية الميللي أمبير(mA) . لذلك، وللتغلب على هذه العقبات ، تم اقتراح دائرة عبور صفرية متزامنة مع مرحلة الجهد الكهربائي لمصدر الجهد في النظام الشبكي الدقيق ، والتي تجعل الشكل الموجي لـ AC بشكل خاص ، خاليًا من التشوه التوافقي المرتفع، تقلل فقدان التحويل وتزيد الكفاءة. يتم إنشاء إشارة عرض نبضة العبور الصفرية لمزامنتها بدقة مع تردد الخط الشبكي الدقيق الذي ينتج من شبكات التبديل والمنطق. يتم استخدام دائرة العبور الصفرية للكشف عن الطور مع التردد، لإنشاء إشارة عبور الصفر ومزامنة زاوية المرحلة بين العاكس والنظام الشبكي الدقيق. في هذه الدراسة، تم تحسين معلمات التحويل العكسي المثلى، بما فيها جهد مصدر الدخل $10kV_{DC}$، ودورة التشغيل 95% ، وتردد التحويل 2 كيلو هرتز وحمولة الشبكة الدقيقة 1000Ω، مع اعتبار العوامل الأخرى. بالإضافة إلى ذلك ، تمّ استخدام مرشح العبور المنخفض LCL للتزاوج بين العاكس والنظام الشبكي، لتحويل الموجة المرافقة إلى موجة جيبية خالصة وتقليل التشوه التوافقي المرتفع. تمّت محاكاة كلٍّ من التصميم المقترح الجديد والتصميم الحالي باستخدام MatLab16.a/Simulink ، أو CAD Capture 16.6 ، و Proteus 8 Professional وKeysight BenchVue . من هذا التحليل ، ومن دون شرط الترشيح ومع ظروف التصفية من (THD)التشوه التوافقي الكلي كانت النتيجة 47.9% و 2.1%، وهي ما يقارب انخفاضاً بمعدل 45% للتشويه التوافقي المرتفع. أظهر تحليل الطور أن مقدار الخطأ في زاوية الطور الجانبي العكسي و زاوية الطور الجانبي للنظام الشبكي الدقيق هما 26.34 و 2.54 درجة على التوالي. أظهرت النتائج النظرية ونتائج المحاكاة والتجربة أن العاكس المصمم حديثًا قد حقق أداءً أفضل من حيث الكفاءة الكلية لتحويل النظام بكفاءة 96.6% وزاوية طور بمقدار 2.54 درجة و THD من حوالي 2.1%. يعدّ PSI المقترح مناسبًا لتطبيقات الشبكة الدقيقة التي يمكن أن تسهم في التحسن الاقتصادي للبلد والعالم ككل.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CSC	Current Source Controller
CSI	Current Source Inverters
DR	Demand Response
DC	Direct Current
ESG	Electrostatic Generator
FFT	Fast Fourier Transform
L	Inductance
LC	Inductance Capacitance
LCL	Inductance Capacitance Inductance
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MCU	Microcontroller Unit
PSI	Phase Synchronous Inverters
PLL	Phase-Locked-Loop
PV	Photovoltaic
PCC	Point of Common Coupling
PFC	Power Factor Correction
PCB	Printed Circuit Bode
PI	Proportional-Integral
PWM	Pulse-Width-Modulated

RE	Renewable Energy
RL	Resistor Inductor
RLC	Resistor Inductor Capacitor
RSI	Resonant Source Inverter
RMS	Root Mean Square
SCS	Silicon Controlled Rectifier
S-PSI	Single Phase-Phase Synchronous Inverters
SPWM	Sinusoidal Pulse Width Modulation
SE	Sustainable Energy
3φ-PSI	Three Phase-Phase Synchronous Inverters
THD	Total Harmonic Distortion
VSC	Voltage Source Controller
VSI	Voltage Source Inverters
ZCS	Zero-Current Switching

LIST OF SYMBOLS

A	Amp
V_{AC}	AC Voltage
P	Actual Power
a_n	Amplitude of the Cosine Wave
a_0	Amplitude of the n^{th} Harmonic Component
b_n	Amplitude of the Sine Wave
Ψ	Angle
X_C	Capacitive Reactance
C	Capacitor
C_L	Capacitor Inductive
V_c	Carrier Signal
I	Current
V_{DC}	DC Voltage
$f(v)$	DC Voltage Function
V_{out}	Desired Average Output Voltage
ΔV_{out}	Desired Output Voltage Ripple
D	Diode
ΔI_{max}	Estimated Inductor Ripple Current
ω	Fundamental Angular Frequency
G	Gate
C_{mn}	Harmonic Co-Efficient
n	Harmonic Number (Only Odd Values of n are Required)
H	Henry
Hz	Hertz
X_L	Inductive Reactance
L	Inductor
V_{in}	Input Voltage
kHz	Kilohertz
I_a	Line Current

$\mathrm{V_a}$	Line Voltage
V_a	Line Voltage
$\mathrm{V_n}$	Magnitude of the N^{th} Harmonic
V_i	Major Harmonic
μF	Microfarads
f	Microgrid Frequency
V_{oa}	Microgrid Voltage
μH	Microhenry
m	Modulation Index
0	Mutual Point
N	Neutral Point
Ω	Ohm
I_{out}	Output Current
$\mathrm{V_{out}}$	Output Voltage
$I_{ab(p\text{-}p)}$	Peak to Peak Current
$\mathrm{V_{ab}}_{(p\text{-}p)}$	Peak to Peak Voltage
θ	Phase Angle
P	Power
Q	Reactive Power
$\mathrm{V_r}$	Reference Signal
$\mathrm{V_r}$	Regulation Voltage
R_L	Resistive Inductive
R	Resistor
f_{res}	Resonance Frequency
S	Switch
f_s	Switching Frequency of the Inverter
SW_r	Switching Ratio
3φ	Three Phase
I_{abc}	Three Phase Current
$\mathrm{V_{abc}}$	Three Phase Voltage
V	Voltage
W	Watt

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Since the global demand for energy is increasing at an exponential rate, the search for alternative energy sources other than fossil fuels and gases is the biggest interrogation. Currently, the demand for power electricity is met by coal, petroleum, hydroelectric and nuclear (Jones, 2017). In a couple of years of 2016-2017, the total energy of the world is obtained by 5% from renewable energy such as solar, wind, geothermal and hydroelectric, 80% from fossil fuels, 5% from nuclear energy and 10% from biofuels (Canada, 2017). Most of the world's energy is utilized for transportation and machinery purposes which cover about 82% of the total energy (Canada, 2017). While only 18% of the total energy is used in the form of electricity (Blanton, 2016). Despite the fact that fossil fuels and gases offer a short-term solution for this energy crisis, they discharge CO2 and other greenhouse gases, which are not environmentally friendly (Banks, 2005 and Sakai, 2015). Therefore, the power microgrid system based on the renewable energy-driven electrostatic generator can be a long-term solution. It is free, available, low cost, high static DC output, easy to handle and environmentally friendly (Rahman, 2016). However, a conversion loss is involved with such a system to deliver electric energy at the load terminal where the source is an electrostatic generator (Rahman et al., 2017a).

The microgrid power system is highly demandable in the new energy management technology. Therefore, the microgrid system is designed for the power supply in a small area which alternates the consumption of fossil fuel and reduces the environmental pollution (Zakariazadeh et al., 2014). The power supply system is an important concern due to the high-level of energy transmission ability of the power microgrid system. Recently, different inverters based on sophisticated switching technique and control topology are studied to ensure the efficient microgrid system (Rahman et al., 2018). In the mentioned literature, the author has described various optimized power inverter topologies as well as switching control techniques to improve the system efficiency by considering the issues of imbalance in the 3φ voltage and current. However, this design is based on unbalanced grid-connected AC to DC inverter (Luo et al., 2017; Blaabjerg et al., 2006).

Phase synchronous inverter (PSI) is an electronic power switching circuit that can convert input DC to an output AC voltage with the same phase and frequency (Gurpinar, 2016). Generally, the inverter can deliver a limited quantity of output power. Being the unconventional concern, several losses are found in the inverters while delivering power to the load circuit. Apart from power losses in the inverter circuit due to the high switching frequency, switching controller also adds some loss in the inverter (Gohi et al., 2016; Cao et al., 2017; Yue et al., 2017; Amin, 2017). In fact, an inverter is an electronic device that transforms the input DC voltage into AC output voltage. Due to this purpose, an electrical inverter mostly draws the DC input power by using a renewable energy source like solar panel which runs the electrostatic generator (Xiong et al., 2016). Since an electrical power inverter gets DC input voltage (standard solar panels which are around 12V to 500V) from renewable energy sources like solar panels or battery, then an electrical inverter transforms the DC voltage to AC voltage of 220V, 240V or 440V with a required frequency of 60Hz or 50Hz. On the other hand, the electrostatic generator (ESG) generates high voltage DC from 4kV to 100kV DC but it generates less current which is in mA range. However, high voltage DC to AC power inverters are widely used for microgrid applications like distribution system. Therefore, ESG-based inverters have applications in microgrid connection of sustainable energy systems (Dasgupta et al., 2013; Yoldaş et al., 2017). In the design of these inverters, the control methods employed are similar to the methods of conventional inverters. The control methods of voltage imbalance and current imbalance are used in practical applications.

To operate DC to AC power inverter, control methods of voltage or current are based on pulse width modulation (PWM) technique. The PWM is a widely used technique where the size of the gate pulses are controlled through different devices (Rahman et al., 2016d). However, the PWM-based inverter is utilized to control the inverter output AC voltage of the inverter regardless of the connected load. Whereas, in a conventional inverter, the output voltage can be modified by allowing the modifications within each load. To this impact of the altering load, the PWM-based inverter specifies the output power by modifying the size of the pulses. Hence, the output power depends on the switching logic and gate pulses that which are regardless of the load coupled to the output terminal. As a result, such a PWM-based inverter provides a well-determined and rated output power (Ramasubramanian, 2017). In general, inverters are designed based on sinusoidal pulse width modulation (SPWM) technique where the control device is utilized as the switch between various circuit topologies. This implies that whether the inverter is a linear or nonlinear operation. The inverter switching circuit is operated by both the voltage and current control mode. Since the control modes are cumbersome, they add further difficulties to operate the switches for the desired applications. In the conversion system, linear and nonlinear methods are found such as synchronized attractors, collision, confusion limit, and branching. However, these conventional techniques have been targeted for systems combined with DC to AC bridge type inverter and DC to AC power factor correction inverters (Rahman et al, 2017).

An extensive number of research works have been studied to outline the development of zero-crossing based voltage source pulse width synchronous inverters circuit. It has been found that the output power range of microgrid-connected conventional inverters is remarkably limited. Therefore, to overcome the challenge of building up an interface circuit which can improve the output voltage and current. it needs further enhancing the efficiency of the conversion system other than the total system.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

Microgrid connected inverter circuit includes the design of the power conversion stages as well as the control algorithms. Power conversion stage consists of all the semiconductor switches, transformers and filters (Yang et al., 2010). Control algorithms involve with a microgrid reference voltage and injected currents, DC link regulated voltage and current, and reference microgrid phase angle and frequency (Chen et al., 2017). In fact, the inverter controller contains multiple stages of inner and outer control loops with the commonly used control bandwidth. Controllers with a high bandwidth limit the timestep for solving the differential equation of inverter design (Bal et al., 2016). A main part of the computation in microgrid-connected inverter simulations is included in the mathematical model leading the operation of a representative switch.

In the case of microgrid applications, an electrostatic generator (ESG) driven by the renewable energy source requires a high voltage gain through the analysis of steady-state, transient and dynamic model based on zero-crossing synchronous method. The energy to be converted to supply AC power for microgrid but such an inversion of the high voltage static DC suffers many problems such as low power quality of waveform, instability between input and output voltage, poor power quality, low power density, low life-cycle of equipment, less-conductivities, high switching loss, higher frequency harmonic distortion and poor phase angle. Therefore, to overcome those issues, a new phase synchronous inverter circuit needs to be proposed for the microgrid system which especially generates the output AC power by reducing the harmonic distortion and switching loss (Bal et al., 2016; Jang et al., 2016; Chen et al., 2017; Agarwal et al., 2017).

Based on the earlier works, it is commonly accepted that the uses and demands of electricity would be exponentially growing. Thus, alternative sources of electricity are important to fulfilling the demand for future electrical power. To answer the growing need for electricity, this research proposes a new work in the field of generating electricity from sustainable energy sources by using electrostatic generators. This challenging task to generate AC power by using the electrostatic generator driven by a renewable energy source mainly focuses on the issues discussed here. It is important to note that an ESG can generate high voltage DC whereby most of the electrical appliances are run by low voltage DC. Subsequently, inverters cannot be avoided in case of using renewable energy source-driven ESG. Again, there are relatively high discharge losses in the ESG when it is associated with other components used in the inverter. Typically, the output voltage and power generation efficiencies depend on the environmental condition. It has high voltage losses in the conversion circuit and consequently, it shortens the circuit lifetime. On the other hand, losses can be reduced by phase synchronization technique which in turn limits the output power of the inverter. Furthermore, it is also necessary to eliminate the influence of the input sources of the inverter and improve the system parameters for the synchronization between the inverter and grid through zero-crossing. Therefore, the inverter needs to be designed in terms of the method that incorporates the stability of the microgrid system.

Based on the literature review, the following issues have been focused as the major challenges of designing the phase synchronous inverter for microgrid systems:

1. High switching loss in the existing inverter switching techniques applied for microgrid systems.
2. The power quality efficiency of an inverter becomes poor due to higher harmonic frequency distortions presence in both sides of the inverter.
3. To make perfect phase synchronization between the inverter and microgrid system is complex.
4. Large and bulky size of the filter in the inverter.
5. Incompatible and high voltage DC output of the electrostatic generator for typical devices and appliances.
6. Due to residual static charge in the electrostatic generator at off condition, high DC voltage exists which damages the electronic circuit.

1.3 RESEARCH OBJECTIVES

This research aims to develop a novel microgrid inverter model for electrostatic generator source based on zero crossing phase synchronization technique. A rigorous switching logic for the phase synchronous inverter has been intended to be developed. The specific objectives of the research are as follows:

1. To design and development of an electrostatic generator as an energy source for the microgrid inverter and optimize the switching circuit parameters of a three-phase microgrid inverter for attaining higher conversion efficiency.