UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF AN INTEGRATED CIRCUIT TOPOLOGY USING MULTILEVEL INVERTER AND MATRIX CONVERTER

AKRAM MOHAMMED AL-MAHROUK

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By

AKRAM MOHAMMED AL-MAHROUK

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To Islam and Muslimeen

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chair : Nashiren Farzilah Binti Mailah, PhD
Faculty : Engineering

Multilevel Inverter (MI) is a device to convert Direct Current (DC) power to Alternating Current (AC) power. The MI is widely used in renewable energy applications such as Photovoltaic (PV) solar cells and wind turbine systems. The main challenges of MIs design are reducing the huge number of Component Count (CC), Total Harmonic Distortions (THD) value and power losses. These challenges are interconnected with the operation challenges such as the types of control algorithms and switching frequencies of MI which overall effect on the MI circuit design and increases the design complexity. The MI can be designed to generate a three-phase output voltage. However, most researchers are more interested in reducing the component count as a single-phase design and then tripled the circuit to generate a three-phase output voltage. Three-Time-Repetition (TTR) is a process of replicating the circuit three times to produce a three-phase output voltage from a single-phase circuit that has contributed to thrice the number of CC.

Two proposed design called Voltage Selection Multilevel Inverter Matrix Converter (VSMIMC) and H-bridge Multilevel Inverter Matrix Converter (HMIMC) was used to solve the TTR problem. The Matrix Converter (MC) was used to share the three input signals into three phase output voltage. For VSMIMC the three input signals of MC ware used as following Maximum Positive Voltage (MPV), Zero Voltage (ZV) and Maximum Negative Voltage (MNV). While for HMIMC, the three input signals are Upper Positive (UP), Middle Positive (MP) and Lower Positive (LP).

The operation of VSMIMC and HMIMC circuits are sophisticated when both of multilevel inverter and matrix converter are connected in series. Therefore, a new proposed control system called Voltage Selection Algorithm (VSA) was formulated to simplify the operation of the proposed circuit. In addition, mix-mode operation using VSA and Nearest Level Control (NLC) was tested to decrease the total harmonic distortions and check the performance flexibility of VSA operation.

The comparison with others' published circuits showed that the proposed VSMIMC and HMIMC had reduced the component count of MI at several different voltage levels. The VSMIMC and HMIMC circuit designs at twenty-five levels had the same number of switches, where below twenty-five levels, the VSMIMC had the lowest number of CC. However, for above twenty-five levels, the HMIMC had the lowest number of CC. The VSMIMC and HMIMC had reduced the CC switches by 75% compared to the traditional MI and 30% compared to the modern designs of MI. The seven levels circuit design of HMIMC gives Total Harmonic Distortion results of 13.38% on simulation model and 12.9% on hardware model.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN TOPOLOGI LITAR TERINTEGRASI MENGGUNAKAN PENYONGSANG BERBILANG ARAS DAN PENUKAR MATRIK.

Oleh

AKRAM MOHAMMED AL-MAHROUK

Julai 2020

Pengerusi : Dr. Nashiren Farzilah Binti Mailah, PhD
Fakulti : Kejuruteraan

Penyonsang Berbilang Aras (PBA) adalah satu peranti untuk menukar kuasa Arus Terus (AT) ke kuasa Arus Ulang-alik (AU). PBA digunakan secara meluas dalam penggunaan tenaga boleh diperbaharui seperti sel suria Photovolta dan sistem turbin angin. Cabaran utama dalam rekaan PBA adalah penggurangan jumlah yang besar Bilangan Komponen (BK), Herotan Harmonik Seluruh (HHS) dan lesapan kuasa. Cabaran ini saling terhubungan dengan cabaran operasi seperti jenis algorithma kawalan dan frekuensi pensuisan PBA yang mana keseluruhan memberi kesan kepada rekaan litar PBA dan meningkatkan kerumitan rekaan. PBA boleh direka untuk menjana voltan keluaran tiga fasa. Namun, kebanyakan penyelidik lebih berminat untuk menggurangkan bilangan komponen sebagai rekaan satu fasa dan menggandakan litar tiga kali untuk menjana voltan keluaran tiga-fasa. Penggulangan-tiga-kali (PTK) ialah satu proses mereplika litar sebanyak tiga kali untuk menghasilkan voltan keluaran tiga-fasa daripada litar satu fasa yang mana akan menyumbang kepada jumlah bilangan komponen tiga kali ganda.

Dua cadangan rekaan bernama Penyongsang Berbilang Aras Penukar Matrik Voltan Pemilihan (PBAPMVP) dan Penyongsang Berbilang Aras Penukar Matrik Jejambat-H (PBAPMJ) telah digunakan untuk menyelesaikan masalah PTK. Penukar Matrik (PM) digunakan untuk berkongsi tiga isyarat masukan kepada voltan keluaran tiga fasa. Bagi PBAPMVP ketiga-tiga isyarat masukan PM digunakan sebagai Voltan Maksimum Positif (VMP), Voltan Sifar (VS) dan Voltan Maksimum Negatif (VMN) Manakala bagi PBAPMJ, ketiga-tiga isyarat masukan adalah Positif Atas (PA), Positif Tengah (PT) dan Positif Bawah (PB).

Operasi litar PBAPMVP dan PBAPMH adalah canggih apabila kedua-dua penyongsang berbilang aras dan penukar matrik bersambung secara sesiri. Oleh itu, satu sistem kawalan baru dicadangkan bernama Algorithma Voltan Pemilihan (AVP) diformulasikan untuk meringkaskan operasi litar yang dicadangkan itu. Tambahan lagi,

operasi mod bercampur menggunakan AVP dan Kawalan Aras Terdekat (KAT) diuji untuk menggurangkan herotan harmonic seluruh dan memeriksa prestasi fleksibiliti operasi AVP.

Perbandingan dengan litar terbitan lain menunjukkan bahawa PBAPMVP dan PBAPMH yang dicadangkan telah menggurangkan bilangan komponen PBA pada beberapa aras voltan yang berbeza. Rekaan litar PBAPMVP dan PBAPMH pada aras dua puluh lima mempunyai jumlah suis yang sama, di mana di bawah aras dua puluh lima, PBAPMVP mempunyai bilangan komponen yang terendah. Namum, untuk aras di atas dua puluh lima, PBAPMH mempunyai bilangan komponen yang terendah. PBAPMVP dan PBAPMH telah menggurangkan suis BK sebanyak 75% berbanding PBA tradisional dan 30% berbanding rekaan PBA moden. Rekaan litar aras tujuh memberi keputusan Herotan Harmonik Seluruh sebanyak 13.38% untuk model simulasi dan 12.9% untuk model perkakasan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Nashiren Farzilah Binti Mailah, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Amran Mohd Radzi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Khair Hassan, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, Ph.D
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 10 December 2020

Declaration by Members of Supervisory Committee

This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________

Name of Chairman of Supervisory Committee: Nashiren Farzilah Binti Mailah

Signature: ____________________

Name of Member of Supervisory Committee: Mohd Amran Mohd Radzi

Signature: ____________________

Name of Member of Supervisory Committee: Mohd Khair Hassan

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LIST OF ABBREVIATIONS

AC	Alternative Current
A_c	Carrier Amplitude
AI	Artificial Intelligence
A_r	Reference Amplitude
BDS	Bidirectional Switch
BJT	Bipolar Junction Transistor
CBSC	Cascaded Bipolar Switched Cells
CC	Component Count
CC BDS	Common Collector Bidirectional Switch
CDCMI	Cascaded Diode Clamped Multilevel Inverter
CE BDS	Common Emitter Bidirectional Switch
CHBMI	Cascaded Half-Bridge Multilevel Inverter
CHMI	Cascaded H-Bridge Multilevel Inverter
CVS-MMC	Cascaded Voltage Source Matrix Multilevel Inverter
DC	Direct Current
DCMI	Diode Clamped Multilevel Inverter
DMC	Direct Matrix Converter
E_{fall}	Fall Energy losses
EP	Equal Phase
E_{rise}	Rise Energy losses
EV	Electrical Vehicles
FACTS	Flixble Alternative Current Transmission System
f_c	Carrier Frequency
FCMI	Flying Capacitor Multilevel Inverter
FF	Feed-Forward
f_r	Reference Frequency
f_{sw}	Switching Frequency
GA	Genetic Algorithm
HEP	Half Equal Phase
HH	Half Hight

HMIMC	H-bridge Multilevel Inverter Matrix Converter
HSF	High Switching Frequency
HVDC	High Voltage Direct Current
Hz	Hirtz
H/L	High or Low
IDE	Integrated Development Environment
IGBT	Insulated Gate Bipolar Transistor
IMC	Indirect Matrix Converter
IoT	Internet of Things
I_{SAV}	Average Switch Current
I/O	Input or Output
J	Joule
L	Constant Changed Voltage Values
LED	Light-emitting Diode
LP	Lower Positive
LSF	Low Switching Frequency
M	State-matrix
m	Milli
M^3C	Modified Multilevel Matrix Converter
MC	Matrix Converter
MI	Multilevel Inverter
MLM	Multilevel Module
MMC	Multilevel Matrix Converter
MNB	Maximum Negative Block
MNV	Maximum Negative Voltage
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MP	Middle Positive
MPB	Maximum Positive Block
MPV	Maximum Positive Voltage
n	nano
NLC	Nearest Level Control
NVC	Nearest Vector Control
p	pico
P_{CL}	Power Conducting Losses

P_{SL}	Power Switching Losses
PSO	Practical SWARM Optimization
PUC	Packed U-Cell
PV	Photovoltaic
PWM	Pulse Width Modulation
R BDS	Reverse Bidirection Switch
Rc	Collector-emitter Resistance
RM	Ringgit Malaysian
RMS	Root Mean Square
RVMI	Reversing Voltage Multilevel Inverter
s	Second
SB	Sub-block
SCSS	Series Connected Switched Source
SHE	Selective Harmonic Elimination
SM	Sub-model
SPMC	Single Phase MC
SSPS	Switched Series Parallel Sources
ST	Sample Time
SVC	Space Vector Control
SVM	Space Vector Modulation
THD	Total Harmonics Distortion
Trad MI	Traditional Multilevel Inverter
TTMI	T-type Multilevel Inverter
TTR	Three Time Repetition
u	micro
UDS	Unidirectional Switch
UP	Upper Positive
V	Voltage
V1	Amplitude voltage of fundamental frequency
V_{CEO}	Collector Emitter Voltage
VSA	Voltage Selection Algorithm
VSMI	Voltage Selection Multilevel Inverter
VSMIMC	Voltage Selection Multilevel Inverter Matrix Converter
W	Watt

Z	Zone
ZV	Zero Voltage
ZVB	Zero Voltage Block
^{o}	Degrees
α	Alpha
Ω	Ohms
2SELG	Two-Switch Enabled Level Generation
5L-MMC	Five-Levels of Multilevel Matrix Converter
9S-MMC	Nine Switches Multilevel Matrix Converter

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, power electronics converters are widely used in generation, transmission and distribution of electricity. In a generation, renewable energy systems need the power electronics converters to convert Direct Current (DC) power to Alternating Current (AC) power in order to make a suitable connection with the electrical grid. The on-grid connection of renewable energy devices have decreased the cost of the renewable energy system set up by excluding the battery and it also helped in electricity bills saving [1]. High power electronics converters have also been utilized in transmission system through the employment of High Voltage Direct Current (HVDC) system [2] and Flexible Alternating Current Transmission Systems (FACTS) [3] devices where power electronics converters have helped in transmitting bulk power over very long distances at higher efficiency, lower losses, and increased the quality of supply and stability respectively. While in distribution, power electronics converters are used in filtration and measurement such as shunt active power filter and smart meter applications [3], [4].

Many of the electrical loads now resort to adopting power electronics converters to regulate the load to operate at high quality and efficiency in applications such as lighting, heating and cooling to name a few. In general, power electronics converters are used in various area of electricity to support the system with smart operations and high efficiency. This has brought the attention to the need to decrease the generation cost and limit the demands load. These issues have been worked on in several different approaches. For example, first, through the usage of renewable energy technologies such as solar cells and wind turbine electrical generations. Second, through the use of energy-saving devices or applications such as Light-emitting diode (LED) light, where each LED light contains a power electronics converter to convert the power from AC to DC. Third, through government policies or incentives, where the government support publics and companies to use hybrid or Electrical Vehicles (EV), as power electronics converters are used to control and operate the electric motors. There are so many more measures taken and not limited to those three.

One of power electronics converters that has gained much attention is Multilevel Inverter (MI), a converter that converts DC power to AC power and has found applications in a wide range covering from low, medium and high voltage applications. Many recent applications have included MI in their designs such as the Internet of Things (IoT) [5], sustainable energies [6], Electrical Vehicles (EVs) [7] and smart grid [8][9]. This means any simple development or improvement in MI circuit design or operation control, it can be directly applied in top current research applications, or in the applications of generation, transmission and distribution of electricity, where some government benefits can be established.

The first generation of MI includes diodes such as diode clamped MI and another design uses capacitors such as flying capacitors MI. The recent designs of MIs focus on the active design of MI, where non-clamped diodes or capacitors are used. The active MI devices reduce the power losses and the cost so that the researchers preferred to use this type of designs. The cascaded H-bridge MI is also one of the first generations of MI, where in this design an isolated transformer is needed. With the inclusion of transformers in the MI design has increased the cost, weight, size and power losses. Therefore, several transformerless MI designs are studied and applied in several types of applications.

Another power electronics converter that has gained popularity is Matrix Converter (MC), an AC to AC power electronics converter and has been widely used in the motor control applications. The traditional MC has nine interconnected bidirectional switches distributed among 3-by-3 matrix shape, with three input signals and three output signals, where any output signal can be connected from any input signal. This is one of the main features of MC that is sharing the input signals to any output loads.

1.2 Problem Statement

There are many problems and challenges faced for MI circuit design to be more feasible in medium and high voltage applications. Based on the literature reviews, there have been found four main problems of MI to be highlighted and then discussed.

First, huge number of switches used in MI has made this to be one of the main challenges in MI as the cost and power losses can be greatly increased. Furthermore, the single-phase MI switches are tripled in order to produce three-phase output voltage, which has made many researchers to focus on reducing the component count (CC) switches. Moreover, the designs that use Bidirectional Switch (BDS) instead of Unidirectional Switch (UDS), means that the researchers need to double the number of switches, therefore, making their designs more complicated and intricate [10], [11].

Second, the Total Harmonics Distortion (THD) value still pose a problem eventhough MI has been used. THD reduction to be within the standard values by increasing the number of output voltage levels is an inefficient solution. Therefore, in the design of MI, the number of levels, the type of operation controls and the switching frequency values that are required, should be balanced and taken into account of each other [12], [13].

Third, the power losses in the MI circuit can be handled in two ways; the number of switches count and the triggering frequency value. The power losses increased when the number of switches and the triggering frequency are increased. Furthermore, the power losses of BDS can be higher than the UDS [14]–[16].

Lastly, fourth, the operation of MI is divided into two types; Low Switching Frequency (LSF) and High Switching Frequency (HSF). HSF consumes higher power losses by the switches, which will decrease the efficiency of the total power converted, especially when a high number of MI switches are used. Additional losses are consumed when the BDS is used instead of UDS [17], [18]. All these problems are interconnected as shown in Figure 1.1.

Moreover, replicating the circuit three times to produce a three-phase output voltage from a single-phase circuit has contributed to thrice the number of CC and is defined as Three-Time-Repetition (TTR). Diminution effect of TTR can reduce the CC switches of MI as reducing each switch will reduce additional components such as the gate drivers circuit.

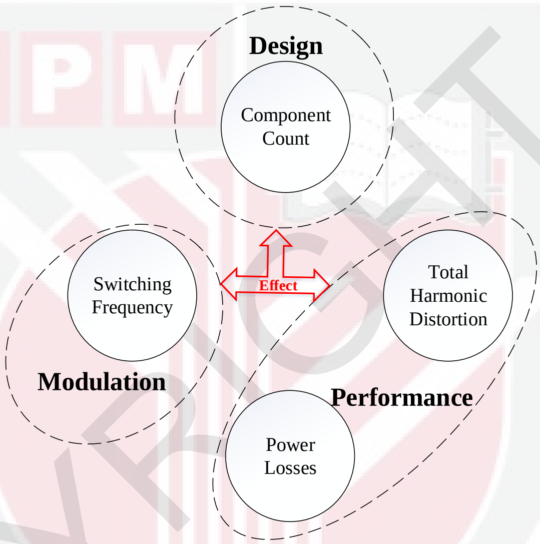

Figure 1.1: Problem statement configuration.

The motivation of this work is to propose an integrated Multilevel Inverter Matrix Converter (MIMC) that has a minimum CC of switching devices and solve the TTR problem that exists in DC to three-phase AC system. This is carry out by proposing two new circuit arrangements with specific control algorithms. The circuit will integrate MI and MC circuits in a compact structure utilizing UDS and positive DC voltage supply. The proposed MIMC will be controlled with specific control algorithm that will minimize THD value. This research aspect is important as the number of components in the converter can increase the cost, size, complexity and power losses.

1.3 Aims and Objectives

The aim of this work is to design, develop and construct an integrated MIMC. The work has the following objectives to accomplish the novelty:

1.To design Voltage Selection Multilevel Inverter Matrix Converter (VSMIMC) that reduce CC and solve TTR.

2.To design H-bridge Multilevel Inverter Matrix Converter (HMIMC) that is improved from VSMIMC with positive DC voltage supply using UDS and H-bridge circuit.

3.To develop Voltage Selection Algorithm (VSA) for controlling VSMIMC and HMIMC circuit.

4.To validate 7L HMIMC controlled by VSA with a laboratory model.

1.4 Scope of the Work

The scope of this work focuses on the DC to AC converter that will generate multilevel output voltages. It consists of MI and MC that will both operate simultaneously in synchronism with each other. For the input voltages to DC side, only equal and symmetrical voltage sources are used. Insulated Gate Bipolar Transistor (IGBT) is selected as the switching device. The proposed circuit will be simulated using MATLAB-Simulink to verify and validate its operation and performance. Later, a laboratory model of the best circuit will be constructed and compared with its simulation model.

The number of the CC of MI switches will be calculated at three-phase operations, where a CC equation is then formulated with respect to the number of output voltage levels. The MI switches for both UDS and BDS types are clearly demonstrated and emphasized. Comparisons of the CC of others' designs and proposed design are carried out and determined. Elimination of the TTR problem is one of the key components in reducing the number of component count.

A new control algorithm will be developed for controlling MI and MC simultaneously. This algorithm will be formulated at LSF and developed for the simulation model using MATLAB-Simulink program. Then, the algorithm will be coded using Arduino for the laboratory model. The results of both simulation and laboratory models are then compared and analyzed.

1.5 Contributions

There are four contributions of this work. They are: -

1. An integrated MIMC circuit has been successfully designed and developed that has solved TTR problem and decrease the total CC of the circuit. This is a novelty because the others' designed circuits have only managed to reduce CC based on single-phase circuit through MI. However, they faced increased number of CC when they replicated the single-phase circuit for three-phase circuit due to TTR.

2. A new design circuit called Voltage Selection Multilevel Inverter Matrix Converter has been successfully filed for patent. This VSMIMC has been designed using BDS. It contains Voltage Selection Multilevel Inverter (VSMI) and MC circuit. The design has been formulated mathematically and simulated in MATLAB-Simulink program successfully. A generalized circuit is then established for a higher number of level upgrades. In addition, the formulation of equations to calculate CC switches with respect to the number of levels has been provided.

3. A second new design circuit has been invented consequently based on VSMIMC, called H-Bridge Multilevel Inverter Matrix Converter and has been successfully simulated and constructed in the lab. This HMIMC design used UDSs instead of BDSs by employing an extra three H-bridge circuits. This design circuit shows better results in reducing the component count. The operating system of HMIMC is verified mathematically and through MATLAB-Simulink simulation. A generalized circuit is then established for a higher number of level upgrades for HMIMC. In addition, the formulation of equations to calculate CC switches with respect to the number of levels has also been provided.

4. A new algorithm system has been designed to operate the VSMIMC and HMIMC circuits using a new proposed algorithm called: Voltage Selection Algorithm. This algorithm provides three-phase controlling steps to synchronize the operation of MI and MC of VSMIMC circuit and also synchronize the operation of MI, MC and H-bridge of HMIMC circuit.

1.6 Thesis Outline

This thesis is organized in five chapters. Chapter 1 gives an introduction to the importance and the application of power electronics converters. It also highlighted the challenges and the problems faced by power electronics converters and the measures taken to solve them. Problem statements, aim, objectives and scope of the work are also defined. The chapter ends with the contributions of the work.

Chapter 2 starts with an overview of different published designs of MI, MC and MIMC. The literature reviews focus on the MI designs that reduced the number of component count and TTR problems. It then follows on the modulation techniques of MI and ended with the performance of the MI.

Chapter 3 provides the theory and methodology of the two proposed circuit designs. The flow chart of this work is also presented. The first proposed circuit VSMIMC is designed, operated, generalized its form and counted mathematically. The second proposed HMIMC is also designed, operated, generalized its form and counted mathematically. Mix-mode operation of HMIMC is explained. The design of the simulation and hardware model are also presented.

Chapter 4 presents the results obtained from MATLAB-Simulink to verify the mathematical operation of VSMIMC and HMIMC. After that, the results of CC comparison in two conditions with a different number of levels are presented. Then the hardware and software implementation results of 7L HMIMC is presented, followed by the hardware costs.

Chapter 5 concludes the research findings on VSMIMC and HMIMC, after that the chapter provides suggestions for future research works based on the study findings.

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BIODATA OF STUDENT

Akram Mohammed Al-Mahrouk was born in Amman, Jordan. He received the bachelor degree in electrical power engineering from the Al-Balqa' Applied University, Faculty of Engineering Technology (BAU-FET), Al-Balqa, Jordan, in 2013, the master degree in electrical and electronics engineering from the Princess Sumaya University for Technology (PSUT), Amman, Jordan, in 2016.

He is currently a PhD student in the Universiti Putra Malaysia (UPM), Selangor, Malaysia. His research focused on the power electronics converters, control and optimisation.

LIST OF PUBLICATIONS

Journals

Akram Mohammed Al-Mahrouk, Nashiren Farzilah Mailah, Mohd Amran Mohd Radzi and Mohd Khair Hassan, "Systematic Review of Multilevel and Matrix Usage in Power Electronics: Circuit Types, System Taxonomy, Applications and Recommendations," *International Review of Electrical Engineering (I.R.E.E.)*, vol. 15 , no. 2 , 2020. (Published)
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Patents

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Conferences

Al-Mahrouk, Akram Mohammed Abdul Aziz and Mailah, Nashiren Farzilah and Mohd Radzi, Mohd Amran and Hassan, Mohd Khair and Wu, Yuan Kang and Hu, Yi Liang (2018) "Modulation index sets of low switching frequency multilevel inverters for wind generation system*". In: 10th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC),* (7-10) Oct. 2018, Kota Kinabalu, Sabah, Malaysia. (pp. 246-251). (Published)

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