

MULTI-STAGE POWER CONVERSION USING MATRIX CONVERTER FOR
SOLID STATE TRANSFORMER TECHNOLOGY

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DEDICATION

This project report is dedicated to my parent, Mr Mohd Noor and Mrs Che Norlia, who are supporting me to continue my study. It is also dedicated to my supportive wife and child, Norhijroton Ramlan, Muhammad Faizzuddin, Ahmad Khairul Ikhwan, Nur Alya Maisarah and Adam Muiz, which is not give-up and always supporting me to finish this study. Not forget to all my friends, classmate, colleague, relatives, and lecturers, thanks and appreciate for the support, encouragement and understandings.

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ABSTRACT

The traditional power transformer typically operated at low frequency with the bulky size either working with step-down voltage or step-up voltage in power system. Aiming to reduce the size of this transformer structure, the solid-state transformer (SST) is suggested. In brief, SST is an ac-to-ac power electronics circuits that operate in high switching frequency offering higher efficiency. Implementation of the smart-grid concept can be made faster than expected with the introduction of SST technology. To-date, there are plenty of power converters that incessant proposed to be used on SST technology. The benefit in term of the structure will give the smaller size and less weight if compare with magnetic transformer. On the other hand, it will impact the cost of equipment and transportation during the installation process. This project will review one of the multi-stage power converters for SST technology of three-phase power system introduced in term of important indices by using a matrix converter. The aims of this project to simulate and analyses the performance of a matrix converter as the ac-ac converter in SST technology.

ABSTRAK

Pengubah kuasa lazim kebiasaannya beroperasi pada frekuensi yang rendah dan bersaiz besar sama ada dalam bentuk voltan langkah turun atau pun voltan langkah naik dalam system kuasa. Dalam mensasarkan pengecilan saiz pengubah kuasa, pendekatan pengubah keadaan pepejal atau dikenali sebagai SST adalah amat disarankan. Secara ringkasnya, pertukaran arus ulang-alik kepada arus ulang-alik dalam litar kuasa elektronik beroperasi dalam suis frekuensi yang tinggi serta memberikan kecekapan yang tinggi. Dengan pengenalan teknologi SST, pelaksanaan konsep grid pintar dapat dilaksanakan dengan lebih pantas daripada apa yang dijangkakan. Sehingga kini, terdapat banyak penukar kuasa sentiasa terus-menerus diusulkan pada penggunaan teknologi SST. Manfaat dari segi struktur, dapat dilihat dari aspek saiz yang lebih kecil dan kurang berat jika dibandingkan dengan pengubah magnet biasa. Antara lain, ianya akan memberi kesan kepada kos peralatan dan pengangkutan semasa proses pemasangan dilaksanakan. Projek ini akan mengkaji semula salah satu penukar kuasa pelbagai peringkat untuk teknologi SST sistem kuasa tiga fasa yang diperkenalkan dari segi indeks penting dengan menggunakan penukar matriks. Matlamat projek ini adalah untuk mensimulasikan dan menganalisis prestasi penukar matriks sebagai penukar au-au dalam teknologi SST.

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LIST OF ABBREVIATIONS

HF	-	High Frequency
LF	-	Low Frequency
SST	-	Solid-State Transformer
AC	-	Alternating Current
HFT	-	High-Frequency Transformer
LFT	-	Low-Frequency Transformer
IGBT	-	Insulated-Gate Bipolar Transistor
FYP1	-	Final Year Project 1
FYP2	-	Final Year Project 2
PWM	-	Pulse Width Modulation
SPWM	-	Sine Pulse Width Modulation
SVM	-	Space Vector Modulation
TPMC	-	Three-Phase Matrix Converter
SPMC	-	Single-Phase Matrix Converter
THD _v	-	Total Harmonic Distortion (voltage)
THD _i	-	Total Harmonic Distortion (current)
FFT	-	Fast Fourier Transform
RMS	-	Root Mean Square

LIST OF SYMBOLS

S_{SST}	-	SST rated power
f_{HFT}	-	Frequency Transformer
V_{ip}	-	SST input line-to-phase voltage
V_{op}	-	Output phase-to-ground voltage
f_i	-	Frequency input
f_o	-	Frequency output
n	-	HFT turns ratio
L_i	-	Input filter inductance
C_i	-	Input filter capacitance
r_p	-	Input filter damping resistor
L_o	-	Output filter inductance
C_o	-	Output filter capacitance
C_{HF}	-	High-Frequency capacitance
μF	-	Micro farad
Ω	-	Ohm
Hz	-	Herzt
V	-	Voltage
Amp	-	Ampere
VA	-	Voltage-Ampere
V_i	-	Voltage Input
V_o	-	Voltage Output

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the power system, the conventional transformer is the main part to convert AC power source either to step-down or step-up either in transmission and distribution. Nevertheless, the size of this transformer is too bulky and heavy. The low efficiency due to high power losses in the form of the hysteresis losses is one of the disadvantages of this low-frequency transformer.

To overcome this weakness solid-state transformer (SST) operated with high frequency is suggested to replace. The HF transformer would reduce the volume and provides galvanic AC-AC conversion(Maharjan *et al.*, 2017). On the other hand, the advantages of this SST technology provided low hysteresis loss and able to reduce the eddy current loss by laminated the core(Sandeep, Shinde and Dake, 2017).

The penetration of renewable energy connected to the smart-grid cause to the high demand application of power electronics offers the space of solid-state transformer technology developing faster as expected. The combination of power converters with HF transformer is needed to make the SST technology working successfully.

The direct converter is also called as matrix converter which is part of the converter can be applied into the SST Technology to perform good AC waveform. A matrix converter consists of bi-directional switches that convert power conversion which has operated rectification and inversion to convert AC-AC. The equivalent circuit matrix converter (indirect matrix converter) shown in Figure 1.1 and the circuit matrix converter (direct converter) shown in Figure 1.2.

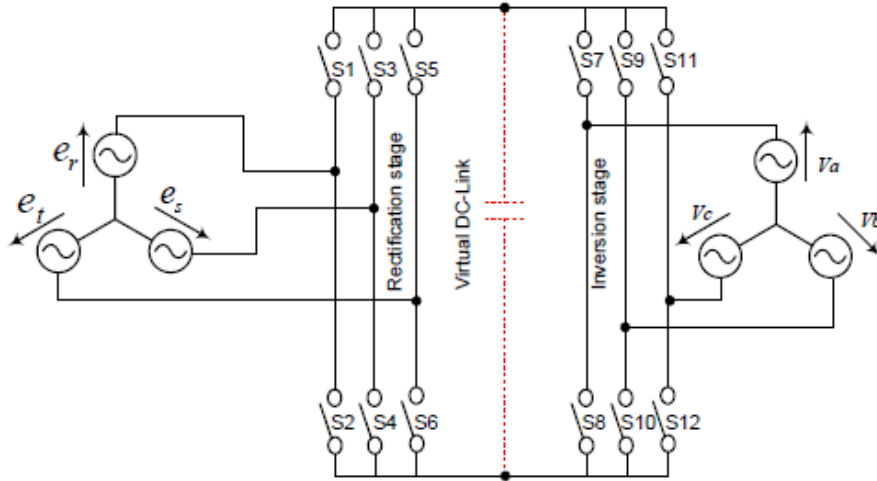


Figure 1.1: Equivalent circuit matrix converter (indirect matrix converter)(Hassan, Sayed and Mohamed, 2017)

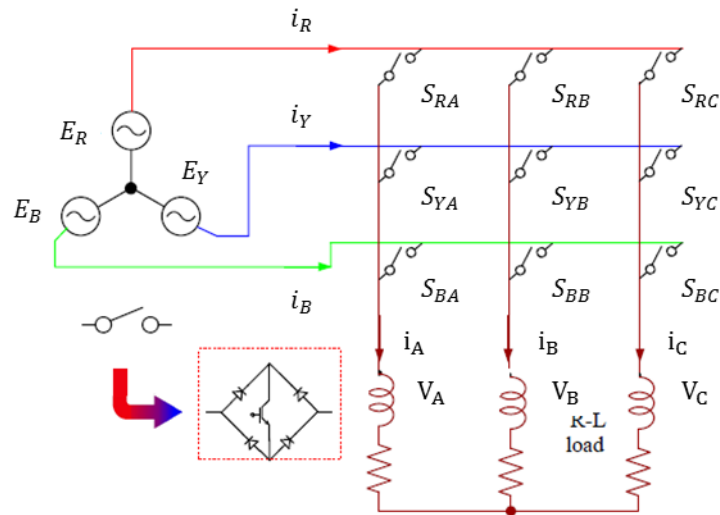


Figure 1.2: Circuit matrix converter(Maharjan *et al.*, 2017)(Kumar, Vyjayanthi, Sreenivasulu, 2016)(Hassan, Sayed and Mohamed, 2017)(Ahuja, Kumar and Agarwal, 2013)(Erdem, Tatar and Sunter, 2005)(Djahbar, Benziane and Zegaoui, 2014)

1.2 Problem Statement

The conventional transformer either step-up or step-down transformer shown in Figure 1.3 from the AC source to the AC load or grid system, the size is bulky and heavy. The expensive of cost not only due to the material, but the transportation cost to bring this conventional transformer to the site also need to reconsider(Hassan, Sayed and Mohamed, 2017; Krishnamoorthy, Enjeti and Sandoval, 2017; Wang, Lei and Liu, 2017).

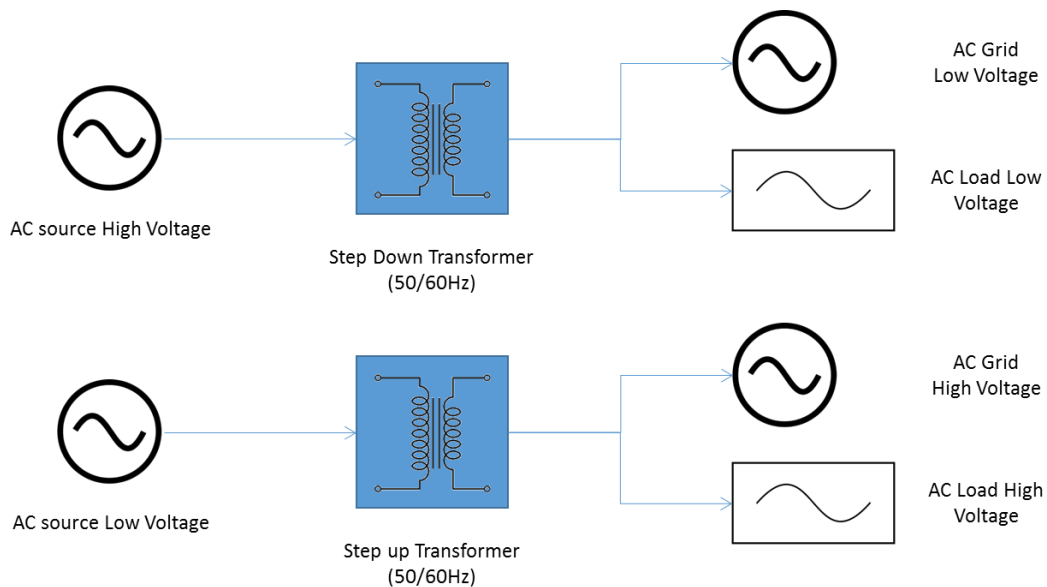


Figure 1.3: Step-up and step-down transformer concept connected from the source to the load or grid

The traditional LF transformer is operating with high losses due to overheating at core and coil whereby produce hysteresis and eddy current finally will be effected to the lower efficiency(Hassan, Sayed and Mohamed, 2017).

1.3 Objectives of Project

The main objectives of this project are:

1. To design multilevel power converters for SST technology of three-phase power system introduced in term of important indices by using matrix converter
2. To simulate and analyses the performance of a matrix converter as the ac-ac converter in SST technology.

1.4 Scope of Project

This project will be focused on matrix converter AC-AC by as the solid-state transformer. The Matlab/Simulink software will be applied to simulate and analyze the results for the three-phase and single-phase matrix converter which is connected to the primary and secondary HF transformer.

1.5 Report Outline

Six chapters involved in this project. Chapter 1 is consists of the introduction of the project that describes the project in general. The subtopic for the problem statement will be discussed based on specific problems that related to this project. In the objectives, will be explained the purpose and agenda to achieve this project. Chapter 2 elaborate literature review that linked to this project. The explanation is based on information which has gathered from the journal, thesis, the internet, reference books and relevant article. Chapter 3 contains the research methodology that explains in detail the overall project flow of multi-stage power conversion using matrix converter for Solid State Transformer technology. Chapter 4 describes the results and analysis and in Chapter 5 contains the conclusion and recommendation of the project. Finally, Chapter 6 will discuss more on project management.

REFERENCES

- Ahuja, R. K., Kumar, P. and Agarwal, L. (2013) 'Modeling and Simulation of Three-Phase Matrix Converter Using Matlab', *International Journal Of Advance Research In Science And Engineering*, 2(10), pp. 220–229.
- Anusuya, R. M. and Saravanakumar, R. (2015) 'Modeling and Simulation of a Single Phase Matrix Converter with Reduce Switch Count as a Buck / Boost Rectifier with Close Loop Control', *International Journal of Research in Computer and Communication Technology*, 3(1), pp. 93–99.
- Chawda, S. (2014) 'Analysis Of Single Phase Matrix Converter', *Journal of Engineering Research and Applications*, 4(3), pp. 856–861.
- Djahbar, A., Benziane, B. and Zegaoui, A. (2014) 'A novel modulation method for multilevel matrix converter', *Energy Procedia*. Elsevier B.V., 50, pp. 988–998. doi: 10.1016/j.egypro.2014.06.118.
- Erdem, E., Tatar, Y. and Sunter, S. (2005) 'Modeling and Simulation of Matrix Converter Using Space Vector Control Algorithm', in *EUROCON 2005 - The International Conference on 'Computer as a Tool'*. Belgrade, Serbia, pp. 1228–1231. doi: 10.1109/EURCON.2005.1630177.
- Hamzah, M. K., Noor, S. Z. M. and Shukor, S. F. A. (2006) 'A new single-phase inverter using single-phase matrix converter topology', in *First International Power and Energy Conference, (PECon 2006) Proceedings*. Putra Jaya, Malaysia, pp. 459–464. doi: 10.1109/PECON.2006.346695.
- Hassan, A. E., Sayed, M. and Mohamed, E. (2017) 'Experimental investigation of Three-Phase AC / AC Matrix Converter Based Space-Vector Modulation With Passive Load', in *2017 Nineteenth International Middle East Power Systems Conference (MEPCON)*. Cairo, Egypt, pp. 577–584. doi: 10.1109/MEPCON.2017.8301239.
- Junhua, H. *et al.* (2017) 'A New Three-Phase "One-Step" Boost Type Matrix Converter', in *2017 Chinese Automation Congress (CAC)*. Jinan, China, pp. 320–324. doi: 10.1109/CAC.2017.8242785.

- Krishnamoorthy, H. S., Enjeti, P. and Sandoval, J. J. (2017) ‘Solid State Transformer for Grid Interface of High Power Multi-Pulse Rectifiers’, *IEEE Transactions on Industry Applications*, 54(5), pp. 5504–5511. doi: 10.1109/TIA.2017.2786257.
- Kumar, Vyjayanthi, Sreenivasulu, N. A. (2016) ‘Modeling and simulation of matrix converter using pi and fuzzy logic controller’, *International Journal of Engineering Sciences & Research Technology*, 5(7), pp. 430–438. doi: 10.5281/zenodo.57000.
- Mahajan, S. *et al.* (2017) ‘Implementation of Matrix Converter for Standalone Power Supplies Employing Induction Generator System’, in *2017 National Power Electronics Conference (NPEC)*. Pune, India, pp. 227–233. doi: 10.1109/NPEC.2017.8310463.
- Maharjan, M. *et al.* (2017) ‘A steady-state equivalent model of solid state transformers for voltage regulation studies’, in *IEEE Power and Energy Society General Meeting*. Chicago, IL, USA, pp. 1–5. doi: 10.1109/PESGM.2017.8274591.
- Matteini, M. (2001) *Control Techniques for Matrix Conv Adjustable Speed Drives*, *PhD Thesis*. University of Bologna, Italy.
- Mohammad Noor, S. Z. *et al.* (2008) ‘Single-phase inverter with fully controllable regenerative capabilities using single-phase matrix converter’, in *2008 3rd IEEE Conference on Industrial Electronics and Applications, ICIEA 2008*, pp. 934–939. doi: 10.1109/ICIEA.2008.4582652.
- Noor, S. Z. M., Hamzah, M. K. and Saparon, A. (2008) ‘Single phase matrix converter for inverter operation controlled using xilinx FPGA’, in *PECon 2008 - 2008 IEEE 2nd International Power and Energy Conference*. Johor Bahru, Malaysia, pp. 764–769. doi: 10.1109/PECON.2008.4762578.
- Patel, P. and Mulla, M. A. (2017) ‘Multi-carrier Pulse Width Modulation for Multimodular Matrix Converter’, in *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. Bangalore, India, pp. 1–6.
- Raju, R., Dame, M. and Steigerwald, R. (2017) ‘Solid-State Transformers using Silicon Carbide- based Modular Building Blocks’, in *IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS)*. Honolulu, HI,

- USA, pp. 1–7. doi: 10.1109/PEDS.2017.8289295.
- Sandeep, U., Shinde, V. and Dake, V. (2017) ‘Modeling and analysis of split core pulse transformer for solid state pulse power modulator’, in *Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*. Coimbatore, India, pp. 1–6. doi: 10.1109/ICECCT.2017.8118032.
- Satish, V., Konathala, S. K. and Kiran, A. U. R. (2014) ‘Design and Implementation of Single Phase Matrix Converter for Cycloconverter Operation’, *International Journal of Engineering Research & Technology (IJERT)*, 3(1), pp. 922–927.
- Shinde, P. B. and Date, T. N. (2017) ‘Pulse Width Modulation Control of 3 Phase AC-AC Matrix Converter’, in *International Conference on Computing Methodologies and Communication (ICCMC)*. Erode, India, pp. 992–997. doi: 10.1109/ICCMC.2017.8282618.
- Srikanth, A. and Kamakotti, P. (2017) ‘AC to AC Conversion Using Single Phase Matrix Converter’, *International Journal of Engineering Science Invention*, 6(11), pp. 29–34.
- Wang, K., Lei, Q. and Liu, C. (2017) ‘Methodology of reliability and power density analysis of SST topologies’, in *IEEE Applied Power Electronics Conference and Exposition - APEC*. Tampa, FL, USA, pp. 1851–1856. doi: 10.1109/APEC.2017.7930950.
- Zainuddin, Z. *et al.* (2018) ‘Solid-state transformer (S2T) of single phase matrix converter’, *International Journal of Power Electronics and Drive Systems*, 9(3), pp. 997–1005. doi: 10.11591/ijpeds.v9n3.pp997-1005.
- Zhang, J. *et al.* (2017) ‘Indirect Matrix Converter Open Circuit Fault Detection and Diagnosis with Model Predictive Control Strategy’, in *2017 IEEE Southern Power Electronics Conference (SPEC)*. Puerto Varas, Chile, pp. 1–5. doi: 10.1109/SPEC.2017.8333580.