

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

MSc THESIS

Ferhat ANDIRIR

**MODELLING AND ANALYSIS OF A DC ELECTRIC SPRING
WITH Z-SOURCE DC-DC CONVERTER**

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS
ENGINEERING**

ADANA-2021

ABSTRACT

MSc THESIS

MODELLING AND ANALYSIS OF A DC ELECTRIC SPRING WITH Z-SOURCE DC-DC CONVERTER

Ferhat ANDIRIR

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Supervisor : Prof. Dr. Mehmet TÜMAY
Year: 2021, Pages: 65
Jury : Prof. Dr. Mehmet TÜMAY
: Assoc. Prof. Dr. Mehmet Uğraş CUMA
: Asst. Prof. Dr. M. Mustafa SAVRUN

In this thesis, a DC-Microgrid that is supplied from renewable energy sources (RESs) is developed and presented. To keep the DC-Microgrid voltage stable, a DC Electric Spring (DCES) is applied to model to remove voltage fluctuations due to intermittent generation of Renewable Energy Sources. The fluctuating voltage of the system input power is absorbed by the series connected Non-Critical Load and DC Electric Spring branch. In order to maintain a stable DC voltage for Critical Load, the voltage quality on Non-Critical Load can be sacrificed. DC Electric Spring tracks the supply side voltage continuously and generates required voltage from battery bank thanks to Half-Bridge DC-DC Converter and Z-Source Converter. The key advantage of Z-Source Converter is the high level voltage gain and satisfies low battery bank costs. System is modelled in MATLAB/Simulink and simulation results are presented.

Keywords: DC Microgrids, DC Electric Spring, Z-Source Converter, Half Bridge Converter

ÖZ

YÜKSEK LİSANS TEZİ

Z-KAYNAK DA-DA DÖNÜŞTÜRÜCÜLÜ DA ELEKTRİK YAYININ
MODELLENMESİ VE ANALİZİ

Ferhat ANDIRIR

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
ELEKTRİK - ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Prof. Dr. Mehmet TÜMAY
Yıl: 2021, Sayfa: 65
Jüri : Prof. Dr. Mehmet TÜMAY
: Doç. Dr. Mehmet Uğraş CUMA
: Dr. Öğr. Üyesi M. Mustafa SAVRUN

Bu tezde, yenilenebilir enerji kaynaklarından beslenen bir Doğru Akım (DA) mikrogrid geliştirilmiş ve sunulmuştur. DA mikro şebeke üzerindeki gerilimi kararlı halde tutabilmek, yenilenebilir enerji kaynaklarının kesikli üretiminden dolayı oluşan gerilim dalgalanmalarını bertaraf edebilmek için sisteme bir DA Elektrik Yay (DCES) uygulanmıştır. Sistem giriş gücündeki gerilim dalgalanmaları seri bağlanmış olan kritik olmayan yük ve DA elektrik yayı kolunda sönümlendirilir. Kritik yük üzerinde kararlı DA gerilimini sürdürebilmek için, kritik olmayan yük üzerindeki güç kalitesinden feragat edilebilir. DA elektrik yayı, kaynak tarafındaki gerilimi sürekli takip eder ve gerekli olan gerilimi yarım köprü DA-DA dönüştürücü ve Z-kaynak dönüştürücü yardımıyla akü grubu tarafından üretir. Z-kaynak dönüştürücünün temel avantajı yüksek seviye gerilim kazancı ve düşük akü maliyetidir. Sistem MATLAB/Simulink ile modellenmiş ve sonuçlar sunulmuştur.

Anahtar Kelimeler: DA Mikrogridler, DA Elektrik Yay, Z-Kaynak Dönüştürücü, Yarım Köprü Dönüştürücü

EXTENDED SUMMARY

Direct Current (DC) power systems have gained importance with rising demand for more efficient power grids. DC power grids provide less number of power conversion stages and improve efficiency. Recent advancements in power electronic technologies enable ease of use and control the power. The innovations in power electronic technologies simplify DC basis electricity generation, distribution, transmission and utilization. These technologies also allow combination of DC power generation like Photovoltaic (PV), DC storage equipments like batteries and most of modern electronic loads like computers, televisions, server centers etc.

While combination of Renewable Energy Sources (RESs), storage equipments and loads improves efficiency and reduces the conversion stages, on the other hand can cause some voltage instability and power quality problems because of intermittent generation of RESs. Energy generation parameters of RESs change continuously. For wind turbines, wind speed is the most important parameter. And so, irradiation and temperature are the most important energy generation parameters for PVs. Irradiation angle, relative humidity, cloudy weather are also important parameters for PVs.

Similar to AC power grids, DC Microgrids are expected to ensure specified voltage quality issues, regulations and voltage tolerances. To cope with voltage instabilities between intermittent RESs and electronic loads, a compensation system is required to remove voltage fluctuations occurred by intermittent generation and instant power changes.

Electric Spring (ES) is an emerging technology comes from mechanical spring in mechanical systems. A spring is an elastic object that has an ability to store mechanical energy. When a mechanical spring is compressed or stretched from its neutral position, it exerts an opposing force proportional to change length. ES concept is the application of Hooke's mechanical spring law into electrical

regime. As mechanical spring mitigates vibrations from mechanical system, ES has ability to step up or step down the voltage level depending on encountered instability on power grid.

Electric Spring (ES) has been proposed to mitigate power quality problems occurred by intermittent nature of RESs, on both AC and DC power grids. ES offers sustainable, reliable and continuous power on demand side.

For widespreading DC Microgrids, DC Electric Spring (DCES) is proposed by (Mok et al., 2015). DCES is an electric active suspension technology for demand side management.

DCES is occurred in a few parts as an ES port, DC-DC converter unit and a battery bank. ES monitors the voltage on demand side and when any fluctuation occurs, it generates the required voltage in required level and polarity and thus removes the fluctuations on power grid.

In DC Microgrids, loads are categorized in two groups as Critical Load (CL) and Non-Critical Load (NCL). Working voltage tolerances and continuity importance are considered while classifying loads as CL and NCL. CL working voltage tolerance is narrower and CLs continuity importance is higher. Servers in data centers is an example of CL. Conversely, NCLs have wider voltage tolerance and their continuity has lower importance. Electrical heaters and water boilers are a few examples of NCLs.

ES can be connected to the Point of Common Coupling (PCC) in two ways. The first one is series with NCL in the form of smart load and the second one is parallel with CL and NCL. While parallel connection offers faster response, series connection proposes lower battery bank capacity. To satisfy power requirements on CL and PCC, the power quality of NCL can be sacrificed. It means that, to maintain stable voltage on CL, NCL voltage can be changed thanks to its wider working voltage tolerances.

ES supplies the required power from a battery bank through DC-DC Converters to PCC. As known to all, battery bank has the highest investment cost

of systems. To reduce the investment cost of battery bank, it is needed to use less battery and improve the voltage amplification ability of DC-DC converter.

DC-DC converter unit must both supply the bipolar output voltage and perform voltage suppression and boosting functions. Thanks to supply bipolar output voltage and ease of control, Half-Bridge DC-DC converter is used in this thesis. Half-Bridge DC-DC Converter uses two switching elements and two capacitances. By changing Duty Cycle (D) of switching signal, the required voltage level and polarity are generated by Half-Bridge DC-DC Converter.

For reducing battery requirements and investment costs, it is needed to higher voltage gain converter. Z-Source DC-DC Converter can boost the input voltage level up to ten times to its output terminal. In addition to this, Z-Source Converter reduces inrush current and improves reliability. Z-Source Converter is consisted of two capacitors and two inductors in X-shaped like a bridge between input source and output terminals.

Z-Source Converter can work in voltage-fed and current-fed mode. In both mode, it can perform buck and boost functions. Thanks to symmetrical connection and circuit shape, it can performs its abilities in bidirectional.

In this thesis, a DCES is modeled to remove fluctuations occurred by intermittent nature of RES. By achieving higher power quality on PCC and CL, it is aimed to reduce cost of battery bank and use less number of battery. Bipolar output voltage, ease of control advantages of Half-Bridge DC-DC Converter is integrated with reduced inrush current, higher reliability and larger range of output voltage gain advantages of Z-Source Converter.

In literature, a few DCES studies are presented. Existing topologies use Half-Bridge or Full-Bridge DC-DC Converters and a battery bank to control voltage level on ES port. Difference of the proposed circuit topology is while still maintaining the stability between tolerances on CL, reduced battery voltage is required. This advantage makes the proposed circuit cost effective compared to existing topologies.

The proposed circuit is modeled and simulated by using MATLAB/Simulink. DCES occurred by Half-Bridge DC-DC Converter integrated with Z-Source DC-DC Converter is run at the same time and the same input voltage source to compare the existing topology occurred by only Half-Bridge Converter and the circuit without DCES. Voltage level of supply side, CL, NCL and behavior of DCES are recorded. The results show that CL voltage level is maintained between tolerances by using 24V battery voltage instead of 72V battery voltage in existing topology. This lower voltage battery requirement makes the proposed circuit topology cost effective.

GENİŞLETİLMİŞ ÖZET

Doğru Akım (DA) güç sistemleri, daha verimli güç şebekelerine talebin artmasıyla önem kazanmıştır. DA güç şebekeleri daha az sayıda güç dönüştürme aşaması sağlar ve verimliliği artırır. Güç elektroniği teknolojisindeki son gelişmeler kullanım kolaylığı ve gücü kontrol etmeyi sağlar. Güç elektroniği teknolojisindeki yenilikler DA elektrik üretimi, dağıtımını, iletimi ve kullanımını kolaylaştırır. Bu teknolojiler aynı zamanda fotovoltaik (PV) gibi DA güç üretimin; bataryalar gibi depolama ekipmanlarının; bilgisayar, televizyon, sunucu merkezleri gibi çoğu modern elektronik yüklerin kombinasyonlarına imkan verir.

Yenilenebilir enerji kaynaklarının, depolama ekipmanlarının ve yüklerin kombinasyonu verimliliği artırıp dönüştürme aşamalarını azaltırken, diğer taraftan yenilenebilir enerji kaynaklarının kesikli üretimlerinden dolayı bazı gerilim dengesizlikleri ve güç kalitesi problemlerine neden olabilir. Yenilenebilir enerji kaynaklarının enerji üretim parametreleri sürekli değişir. Rüzgar türbinleri için, rüzgar hızı en önemli değişkendir. Benzer şekilde ışınım ve sıcaklık fotovoltaikler (PV) için en önemli enerji üretim parametreleridir. Işınım açısı, bağıl nem, bulutlu hava gibi değişkenler yine fotovoltaikler için önemli değişkenlerdir.

Alternatif Akım (AA) güç şebekelerinde olduğu gibi, DA mikro şebekelerin de belirlenen gerilim kalitesi, düzenlemeleri ve gerilim toleranslarını sağlaması gerekir. Kesikli yenilenebilir enerji kaynakları ve elektronik yükler arasındaki gerilim dengesizlikleriyle başa çıkabilmek için aralıklı üretim ve anlık güç değişimlerinden kaynaklanan gerilim dalgalanmalarını giderebilmek için bir kompanzasyon sistemi gereklidir.

Elektrik Yay, mekanik sistemlerdeki mekaniksel yaylardan gelen yeni gelişmekte olan bir teknolojidir. Yay, mekanik enerjiyi depolayan elastik bir nesnedir. Bir mekaniksel yay nötr konumundan sıkıştırıldığında veya sündürüldüğünde, gerilme miktarıyla orantılı olarak bir karşıt kuvvet uygular. Elektrik yayı konsepti, Hooke'un mekanik yay yasasının elektriksel rejime

uygulanmasıdır. Mekanik yayın, mekaniksel sistemlerden titreşimleri uzaklaştırdığı gibi, elektrik yayı da elektrik şebekesinde karşılaşılan kararsızlığa bağlı olarak gerilim seviyesini yükseltme ve düşürme yeteneğine sahiptir.

Elektrik yayı, hem AA hem de DA güç şebekelerinde yenilenebilir enerji kaynaklarının kesikli doğası nedeniyle oluşan güç kalitesi problemlerini azaltmak için sunulmuştur. Elektrik yayı talep tarafında sürdürülebilir, güvenilir ve sürekli güç sunar.

Yaygınlaşan DA mikro şebekeler için DA elektrik yayı önerilmiştir (Mok et al., 2015). DA elektrik yayı, talep tarafı güç yönetimi için elektrik aktif süspansiyon sistemidir.

DA elektrik yayı, elektrik yayı portu, DA-DA dönüştürücü ünitesi ve akü grubu olmak üzere birkaç parçadan oluşur. Elektrik yayı, talep tarafındaki gerilimi izler ve herhangi bir dalgalanma meydana geldiğinde, ihtiyaç duyulan seviyede ve polaritede gerekli gerilimi üretir ve elektrik şebekesi üzerindeki dalgalanmaları ortadan kaldırır.

DA mikro şebekelerde yükler, kritik yükler ve kritik olmayan yükler olarak iki gruba ayrılır. Yükler kritik ve kritik olmayan yükler olarak sınıflandırılırken çalışma gerilimi toleransları ve süreklilik önemi dikkate alınır. Kritik yükler için çalışma gerilim toleransı daha dar ve süreklilik önemi daha yüksektir. Veri merkezlerindeki sunucular, kritik yüklerdir. Diğer taraftan, kritik olmayan yükler, daha geniş gerilim toleransına sahiptir ve sürekliliği daha düşük öneme sahiptir. Elektrikli ısıtıcılar ve su kazanları kritik olmayan yüklerin birkaç örneğidir.

Elektrik yayı, ortak bağlantı noktasına iki şekilde bağlanabilir. Birincisi, kritik olmayan yük ile seri şekilde, akıllı yük formunda ve ikincisi kritik ve kritik olmayan yük ile paralel şekildedir. Paralel bağlantı daha hızlı yanıt sunar, seri bağlantı daha düşük batarya gereksinimi sunar. Kritik yük ve ortak bağlantı noktasındaki güç gereksinimlerini karşılamak için kritik olmayan yükün güç kalitesinden ödün verilebilir. Bu, kritik yük üzerinde sabit gerilimi sürdürmek için

kritik olmayan yükün daha geniş çalışma gerilim toleransı sayesinde geriliminin değiştirilebileceği anlamına gelir.

Elektrik yayı, gerekli gücü bir batarya bankasından DA-DA dönüştürücüler aracılığıyla ortak bağlantı noktasına sağlar. Bilindiği üzere batarya bankası en yüksek sistem yatırım maliyetine sahiptir. Akü grubunun yatırım maliyetini düşürmek için daha az batarya kullanılması gerekir ve DA-DA dönüştürücülerin gerilim yükseltme kabiliyetinin artırılması gerekir.

DA-DA dönüştürücü ünitesi, hem gerilim yükseltme ve düşürme işlevlerini gerçekleştirmeli hem de iki kutuplu çıkış gerilimi sağlamalıdır. İki kutuplu çıkış gerilimi sağlaması ve kontrol kolaylığı sayesinde bu tezde yarım köprü DA-DA dönüştürücü kullanılmıştır. Yarım köprü DA-DA dönüştürücü iki anahtarlama elemanı ve iki kapasitans kullanır. Anahtarlama sinyalinin görev döngüsü (D) değiştirilerek, gerekli gerilim seviyesi ve polarite yarım köprü DA-DA dönüştürücü tarafından üretilir.

Pil gereksinimlerini ve yatırım maliyetlerini azaltmak için daha yüksek gerilim kazanımlı dönüştürücüye ihtiyaç vardır. Z-kaynak DA-DA dönüştürücü giriş gerilim seviyesini çıkış terminalinde on kata kadar arttırabilir. Buna ek olarak, Z-kaynak DA-DA dönüştürücü, ani akımı azaltır ve güvenilirliği artırır. Z-kaynak DA-DA dönüştürücü giriş ve çıkış terminalleri arasında bir köprü gibi X şeklinde iki kapasitör ve iki indüktörden oluşur.

Z-kaynak dönüştürücü, gerilim beslemeli ve akım beslemeli olarak çalışabilir. Her iki modda da gerilim yükseltme ve düşürme işlevlerini gerçekleştirebilir. Simetrik bağlantı ve devre şekli sayesinde yeteneklerini çift yönlü olarak gerçekleştirebilir.

Bu tezde, yenilenebilir enerji kaynaklarının kesikli doğası nedeniyle oluşan dalgalanmaları gidermek için bir DA elektrik yayı modellenmiştir. Ortak bağlantı noktasında ve kritik yük üzerinde daha yüksek güç kalitesi elde edilerek batarya maliyetlerinin düşürülmesi ve daha az sayıda batarya kullanılması amaçlanmaktadır. Yarım köprü DA-DA dönüştürücünün iki kutuplu çıkış gerilimi

ve kolay kontrol kolaylığı avantajlarıyla, Z-kaynak dönüştürücünün düşük ani akım, daha yüksek güvenilirlik ve daha yüksek gerilim kazanım avantajları birleştirilmiştir.

Literatürde, birkaç DA elektrik yayı çalışması sunulmaktadır. Mevcut topolojiler elektrik yayı portundaki gerilim seviyesini kontrol etmek için yarım köprü veya tam köprü DA-DA dönüştürücüler ve akü bankası kullanır. Önerilen devre topolojisinin farkı, kritik yük üzerindeki kararlılığı toleranslar içinde korurken, daha düşük batarya gerilimi gerektirir. Bu avantaj, önerilen devreyi mevcut topolojilere kıyasla daha uygun maliyetli hale getirir.

Önerilen devre, MATLAB/Simulink kullanılarak modellenmiş ve simule edilmiştir. Z-kaynak DA-DA dönüştürücü ile entegre edilmiş yarım köprü DA-DA dönüştürücü ile oluşan DA elektrik yayı, sadece yarım köprü DA-DA dönüştürücü ile kurulmuş mevcut DA elektrik yayı ve hiç elektrik yayı kullanılmayan devreler ile karşılaştırmak amacıyla aynı anda ve aynı giriş gerilim sinyaliyle çalıştırılmıştır. Besleme tarafı gerilimi, kritik yük, kritik olmayan yük gerilimleri ve DA elektrik yayı davranışları kaydedilmiştir. Sonuçlar, kritik yük gerilim seviyesinin mevcut topolojide 72V batarya yerine 24V batarya gerilimi kullanılarak toleranslar arasında korunduğunu göstermektedir. Bu düşük gerilim batarya gereksinimi , önerilen devre topolojisini uygun maliyetli hale getirir.

ACKNOWLEDGEMENTS

I would like to express my heartfelt thanks to my supervisor Prof. Dr. Mehmet TÜMAY for his supervision, guidance, encouragements, and continuous confidence in me throughout this thesis. It has been a great honor to have Prof. Dr. Mehmet TÜMAY as supervisor.

I would like to thank Assoc. Prof. Dr. Mehmet Uğraş CUMA for his guidance, valuable advices and strong technical support.

I am also grateful to Asst.Prof.Dr. Murat Mustafa SAVRUN for his extremely valuable guidance and suggestions. His continuous support helped me to finish this thesis.

Finally, I would like to express my deepest gratitude to my father, my mother and my sister for their patience, encouragement and continuous support.

CONTENTS	PAGE
ABSTRACT.....	I
ÖZ	II
EXTENDED SUMMARY.....	III
GENİŞLETİLMİŞ ÖZET	VII
ACKNOWLEDGEMENTS	XI
CONTENTS.....	XII
LIST OF TABLES	XIV
LIST OF FIGURES	XVI
LIST OF SYMBOLS	XVIII
LIST OF ABBREVIATIONS.....	XIX
1. INTRODUCTION	1
1.1. Overview.....	1
1.2. Scope of the Thesis	2
1.3. Outline of the Thesis	3
2. LITERATURE REVIEW	5
2.1. DC MICROGRIDS	8
2.2. ELECTRIC SPRINGS	10
2.3. DC ELECTRIC SPRINGS.....	12
2.4. DC-DC CONVERTERS	15
2.4.1. Buck Converter	15
2.4.2. Boost Converter	17
2.4.3. Buck-Boost Converter	18
2.4.4. Half-Bridge Converter	20
2.4.5. Full-Bridge Converter.....	21
2.5. Z-SOURCE CONVERTERS	22
3. POWER CIRCUIT MODELING	31
3.1. Power Circuit Modeling of DC Electric Spring (DCES)	34

3.2. Power Circuit Modeling of DC-DC Converter	38
4. CONTROLLER MODELING.....	41
5. SIMULATION RESULTS	43
5.1. Case 1.....	46
5.2. Case 2.....	53
6. CONCLUSION.....	59
REFERENCES	61
CURRICULUM VITAE.....	65



LIST OF TABLES	PAGE
Table 2.1. Qualifications of Series ES and Shunt ES	8
Table 2.2. DC Applications and their voltage levels (Hashem et al., 2018).....	10
Table 2.3. Comparison of series type ES and shunt type ES	13
Table 2.4. Voltage Transfer Ratio of Z-Source DC-DC Converter	24
Table 3.1. System Specifications of Experiment	37
Table 3.2. Parameters of Half-Bridge Converter	39
Table 3.3. Parameters of Z-Source Converter.....	40
Table 4.1. Parameters of PI Controller	42
Table 5.1. Parameters of Proposed System.....	45
Table 5.2. Comparison of Circuit Parameters	51
Table 5.3. Total Cost of Existing Topology.....	51
Table 5.4. Total Cost of Proposed Topology	52



LIST OF FIGURES	PAGE
Figure 2.1. Block Diagram of (a) Series Type ES (b) Shunt Type ES	7
Figure 2.2. DC Microgrid.....	9
Figure 2.3. Different types of AC-ES (a) ES-I (b) ES-II (c) ES-III	11
Figure 2.4. (a) Series ES and (b) Shunt ES	12
Figure 2.5. The most common types of DC-DC Converters.....	15
Figure 2.6. Circuit diagram of Buck Converter.....	16
Figure 2.7. Circuit diagram of Boost Converter.....	17
Figure 2.8. Circuit diagram of Buck-Boost Converter.....	19
Figure 2.9. Circuit diagram of Half Bridge Converter	21
Figure 2.10. Circuit diagram of Full Bridge Converter.....	22
Figure 2.11. Z-Source DC-DC Converter topology	23
Figure 2.12. Two operating modes of Z-Source DC-DC Converters (a) Voltage-fed (b) Current-fed	23
Figure 2.13. (a) State1: S1 is ON, S2 is OFF (b) State2: S1 is OFF, S2 is ON.....	25
Figure 2.14. Quasi-Z-Source converter (a) Continuous current (b) Discontinuous current	27
Figure 2.15. Circuit Diagram of Quasi Z-Source (a) S is ON state (b) S is OFF state.....	28
Figure 3.1. Power Circuit Model of The Proposed System.....	33
Figure 3.2. Power Circuit Model of Proposed DC-DC Converter	39
Figure 4.1. Controller Circuit Model of Proposed DC-DC Converter	41
Figure 4.2. Schematic Diagram of PI Controller.....	41
Figure 5.1. Circuit Diagram of Proposed System	43
Figure 5.2. Circuit Diagram of Existing Topology (Mok et al., 2016)	44
Figure 5.3. Voltage Levels of Existing Topology without Z-Source DC- DC Converter.....	47

Figure 5.4.	Voltage Levels of Loads without DCES.....	48
Figure 5.5.	Voltage Levels of Proposed Topology	49
Figure 5.6.	Comparison of Voltage Levels of Topologies	50
Figure 5.7.	Voltage Levels of Existing Topology without Z-Source DC- DC Converter by changing NCL	55
Figure 5.8.	Voltage Levels of Loads without DCES by Changing Load.....	56
Figure 5.9.	Voltage Levels of Proposed Topology by Changing Load.....	57
Figure 5.10.	Comparison of Voltage Levels of Topologies by Changing Load	58

LIST OF SYMBOLS

V_s	:	Input voltage
V_o	:	Output voltage
f	:	frequency
I_s	:	Input Current
I_o	:	Output Current
V_{bat}	:	Battery Voltage
D	:	Duty cycle
S	:	Switch
C	:	Capacitance
R	:	Resistance
L	:	Inductance
V_L	:	Inductance Voltage
I_L	:	Inductance Current
V_C	:	Capaitance Voltage
I_C	:	Capacitance Current
I_L	:	Inductor current
L_Z	:	Z-Source Inductance
C_Z	:	Z-Source Capacitance
R_d	:	Distribution Line Resistance
R_{CL}	:	Critical Load Resistance
R_{NCL}	:	Non-Critical Load Resistance
K_p	:	Proportional Gain
K_i	:	Intagral Gain

LIST OF ABBREVIATIONS

AC	:	Alternating Current
ACES	:	Alternating Current Electric Spring
CL	:	Critical Load
DC	:	Direct Current
DCES	:	Direct Current Electric Spring
DG	:	Distributed Generation
DSM	:	Demand Side Management
ES	:	Electric Spring
ESS	:	Energy Storage System
NCL	:	Non-Critical Load
PCC	:	Point of Common Coupling
PV	:	PhotoVoltaic
RES	:	Renewable Energy Source

1. INTRODUCTION

1.1. Overview

With the rising demand for more efficient power grids, using Direct Current (DC) power systems and DC microgrids for electricity generation, distribution, transmission and utilization have gained importance. By the advancement in power electronic technologies, DC basis electricity generation and storage equipment like Photovoltaic (PV) cells, fuel cells, batteries and some capacitive alternatives are combined with directly DC consumer loads such as computers, televisions, servers in data centers and electronic appliances. Combination of DC basis generation, storage and loads reduces conversion losses DC-AC or AC-DC.

Integration of Renewable Energy Sources (RESs) into DC Microgrids can cause some voltage instability and power quality problems because of intermittent nature of RESs. Recognizedly, RESs like PVs, wind turbines cannot produce electricity continuously. Irradiation and temperature are the main factors to specify power generation of PVs and these parameters are changing continuously. Sun intensity, cloudy weather, irradiation angle, relative humidity, temperature and seasons effect solar panels power generation. For example, during midday, the sun is on its peak, power generation increases. Some partial shading conditions like dust, trees, cloudy weather also effects PV generation negatively. In summer days, temperature increases and power production can be reduced by 10% to 25% (Gordo et al., 2015).

Similar to AC power grids, DC microgrids are expected to ensure specified regulations and voltage tolerances. To cope with voltage stability problems on demand side, a compensation system is needed to remove undesired effect of RESs instant power changes.

Electric Spring (ES) concept comes from mechanical springs. A spring is an elastic object that stores mechanical energy. When a mechanical spring is

compressed or stretched from its neutral position, it exerts an opposing force proportional with length change. The application of Hooke's law in mechanical spring into electric regime is proposed (Hui et al., 2012). As mechanical springs mitigate vibrations from mechanical system, ES can step up or step down the voltage depending on encountered instability on power network.

Because of the intermittency of RESs some voltage quality problems occur on power grid. By penetrating RESs like wind farms, PV arrays are enhancing voltage generation, on the other hand the probability of occurrence of voltage sag, voltage swell, voltage oscillation problems are increasing.

Electric Springs (ESs) have been proposed to mitigate power quality problems on AC and DC power systems to ensure sustainable, reliable and continuous voltage and current (and also frequency for AC systems) on demand side.

For that purpose, Direct Current Electric Spring (DCES) has been introduced to apply into DC microgrids (Mok et al., 2015).

DCES is occurred in a few parts. These are ES port, DC-DC converter and a battery port. As is known to all, battery bank has one of the highest investment costs of systems. To reduce investment cost of battery bank, it is required to use less battery and improve higher level voltage gain DC-DC converter.

Compared to the existing DC-DC converter circuits, Z-Source DC-DC converter has many advantages over others. It can reduce in-rush current, provide larger range of output DC voltage and improve reliability (Fang, 2008).

1.2. Scope of the Thesis

In this thesis, a DC Microgrid that is supplied from Renewable Energy Sources (RESs) is modelled. The DC Microgrid which includes Critical Load and Non-Critical Load is designed to analyze power quality issues like voltage and current in different circumstances of intermittent generation of RESs. To ensure the power quality on Point of Common Coupling (PCC), loads are categorized in two

groups as Critical Loads (CLs) and Non-Critical Loads (NCLs). Working voltage tolerances and continuity importance are considered while classifying loads as CL and NCL. To satisfy power requirements on CL and PCC, power quality on NCL can be sacrificed. DCES is connected series with NCL in the form of smart load and voltage fluctuations originated from discontinuous supply side voltage are compensated on this smart load branch.

DCES has a power conversion unit and a battery bank to feed or absorb power on capacitive element according to PCC voltage. Power conversion unit named as DC-DC Converter tracks the voltage level on PCC and generates the power with required voltage level to ES port. DC-DC converter can also change the voltage polarity to adjust NCL voltage and thus maintains the voltage level on CL and DC bus stable. A few different types of DC-DC Converter can be used to feed power to ES port.

A Half-Bridge DC-DC Converter integrated with Z-Source DC-DC converter is proposed in this study. By the low instrument cost and easy control advantages of Half-Bridge DC-DC Converter are combined with the reduced inrush current, larger voltage gain and improved reliability advantages of Z-Source DC-DC Converter. While generating bipolar voltage on ES port by Half-Bridge DC-DC Converter, it can be reached the voltage level up to ten times of battery bank thanks to Z-Source DC-DC Converter on ES port.

1.3. Outline of the Thesis

The main objective of this thesis is to implement a new type of DC-DC Converter for a DCES to increase efficiency and ease of control while decreasing cost. For this purpose, Half-Bridge DC-DC Converter and Z-Source DC-DC Converter are combined together to take the advantages of both converters. A DC-Microgrid system consisting of PV, CL, NCL and DCES with proposed DC-DC converter is modeled and simulated by using MATLAB/Simulink.

The next sections of this thesis as follows;

Chapter 2 gives the literature review about DC Microgrids, DCES, DC-DC Converters and Z-Source DC-DC Converters.

In chapter 3, Modelling of Power Circuit and parameter calculations are presented.

In chapter 4, Controller Modelling of proposed circuit is presented.

In chapter 5, Simulation Results of proposed circuit and existing topology are presented in detailed and performances are compared.



2. LITERATURE REVIEW

A Microgrid is a local energy grid that includes distributed generation, energy storage, local loads and system control ability. Nowadays, with the increase of DC sources and DC loads, DC Microgrids have gained importance and become more popular in transmission and distribution (Jeung et al., 2019). DC Microgrids are thought that have been emerged technology for smart homes, commercial and residential applications (Li et al., 2016). By the advantages of DC nature of Renewable Energy Sources (RESs) like Photovoltaics (PVs); Energy Storage Systems (ESSs) like batteries and super-capacitors; DC loads like computers, electronic appliances, sources and consumers can be connected in a subsystem. DC Microgrids can reduce conversion stages and conversion losses and improve energy efficiency. The DC basis system reduces complexity and cost; increases efficiency and enables use of highly efficient smart household loads (Karami and Cuzner, 2016). By comparison with AC Microgrid, DC Microgrid has not required phase monitoring and frequency of voltage, and it shows that it is more controllable and useful, so DC Microgrid is more convenient for using in distributed power generation and utilization. DC Microgrids have also more advantages in simplification of power conversion process and increase the system conversion efficiency (Zhao et al., 2017).

Although DC Microgrids do not require frequency and phase synchronization, it is still required a balance between sources and loads. Without appropriate control, both intermittent generation of renewable energy sources and load change in demand side can cause instantaneous power imbalance which would affect DC-bus voltage and hence power quality. Traditionally, this power quality problems are mitigated by energy storage equipment. Recently, with a new smart grid technology named as Electric Spring (ES) has been increasingly used to mitigate the power imbalance problems with reduced battery capacity requirements of energy storage systems (Chen et al., 2017).

Electric Spring (ES) concept has been derived based on mechanical spring. ES can be applied in AC or DC grid for demand side management and improves power quality (Hashem et al., 2018). This type of smart grid technology is named as AC Electric Spring (ACES) when applied in AC power systems and DC Electric Spring (DCES) when applied in DC power systems. ES separates the loads in two categories as Critical Loads (CLs) and Non-Critical Loads (NCLs) according to their voltage tolerances. CL voltage requirement is more precise and can continue working in a narrow voltage fluctuation range. To keep the stable voltage on CL and Point of Common Coupling (PCC), DCES transfers some of energy fluctuations from PCC to NCL, and remaining fluctuation is removed by battery bank. This technology enables fast and flexible energy storage and reduces the battery bank capacity (Zha et al., 2019).

DCES has a series type which can provide a bipolar voltage output DC-DC Converter connected series with a Non-Critical Load (NCL), and a shunt type which provides unipolar voltage output DC-DC converter directly connected to PCC as shown in Figure 2.1(a) and Figure 2.1(b). Both types of DCES can provide a long-term real power support and remove the harmonics (Wang et al., 2017).

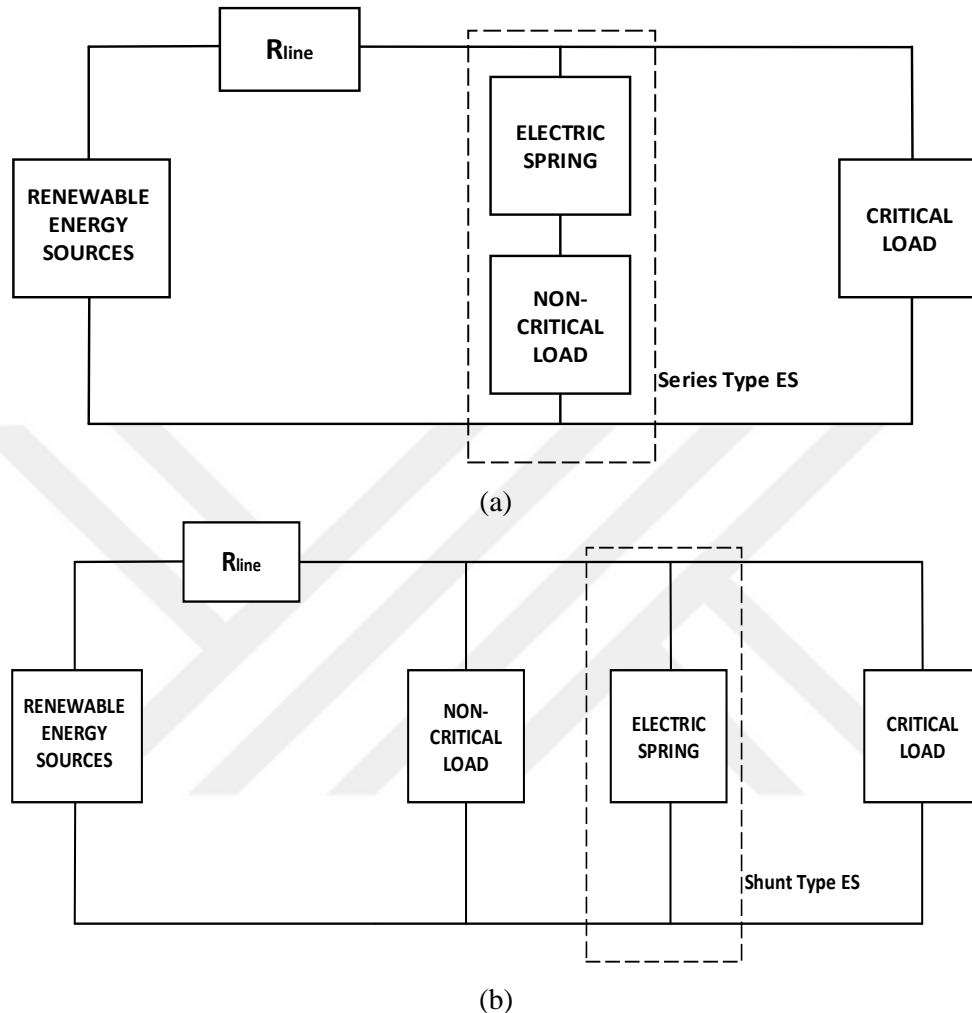


Figure 2.1. Block Diagram of (a) Series Type ES (b) Shunt Type ES

Series type ES is fundamentally a controllable voltage source. It is connected series with Non-Critical Load (NCL) in a form of smart load. Smart load can carry out automatic load adjustment by changing ES voltage. Smart load current is reduced by applying ES Voltage >0 or increased by making ES Voltage <0 . Series ES provides indirect current compensation to maintain stable voltage on PCC at predefined level. Shunt type ES is fundamentally a controllable current source. It is directly connected on PCC. Shunt ES provides direct current

compensation. It absorbs or injects current to PCC to maintain stable voltage. Qualifications of Series ES and Shunt ES is shown in Table 2.1. (Wang et al., 2015).

Table 2.1. Qualifications of Series ES and Shunt ES

Series ES	Shunt ES
✓ DC bus voltage regulation	✓ DC bus voltage regulation
✓ PCC harmonic compensation	✓ PCC harmonic compensation
✓ Controlable voltage source	✓ Controllable current source

To ensure stable voltage on PCC, it is needed to feed ES port with required voltage level and polarity. Half-bridge DC-DC Converter is implemented to ES port thanks to its polarity changing ability and controlled by two switching element advantages (Mok et al., 2016).

In this paper, the main objective is maintaining stable voltage on PCC by using DCES with lower cost battery bank. For this purpose, it is needed to increase voltage gain to use less battery. Reduced in-rush and harmonic current, providing larger range of output DC voltage (up to 10 times) and improved reliability advantages make the Z-Source DC-DC Converter attractive (Fang and Ji, 2008).

2.1. DC MICROGRIDS

Direct Current (DC) power system was invented by Tomas Alva Edison and used for commercial and residential purposes in New York City in 1882. Nevertheless, DC power utility system lasted very short time period and replaced by Alternating Current (AC) in the early 1900s (Mok et al., 2016). DC power system has a disadvantage of high line losses due to low-voltage transmission. On the other hand, AC power system has an advantage of low-loss high-voltage power transmission with the help of voltage transformer.

By the advancement in power electronic technologies, rising demand for more efficient and smarter power grids, DC power systems have gained importance once more again. DC power grid is more direct and effective system than AC power grid for most of electronic application that use DC voltage supply directly. DC Microgrids have especially gained importance with the penetration on PVs to electricity transmission and distribution systems. Many Renewable Energy Sources (RESs) like PVs, fuel cells generate power in DC form. Most electronic loads such as computers, LEDs and data servers, electric vehicles and storage devices like batteries require DC voltage supply as shown in Figure 2.2. Direct use of DC power provides to use less energy conversion stage and this reduces cost and improves system efficiency. Also, compared with AC grid, DC Microgrid has not required phase and frequency synchronization. Thus, DC Microgrids are highly efficient way to deliver power in future smart grids.

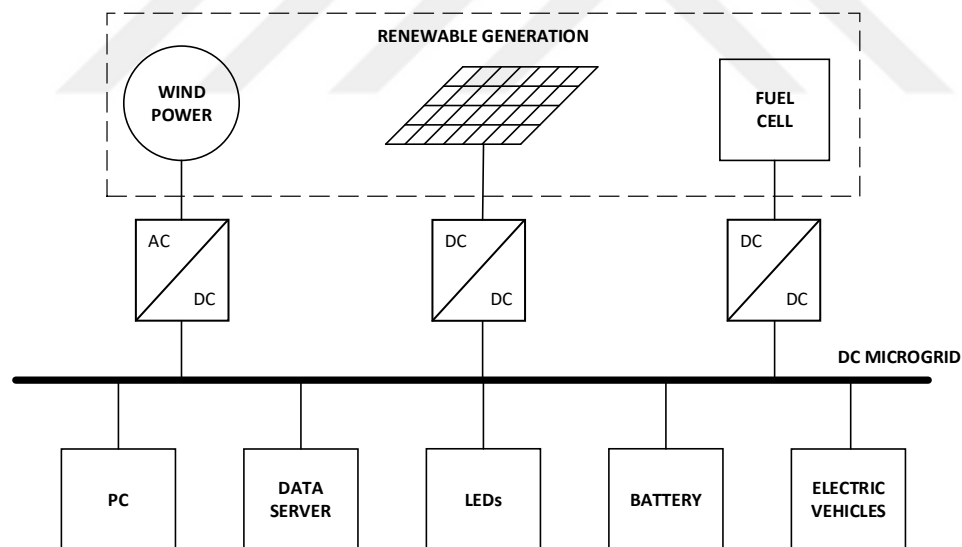


Figure 2.2. DC Microgrid

Different voltage levels like 48V, 120V, 230V, 326V have been proposed in different studies as shown in Table 2.2 (Wang et al., 2015). Between different voltage levels, 380V DC Microgrid is considered as the most efficient and economical and 48V DC Microgrid is the best option for safety and efficiency (Xu and Cheng, 2011).

Table 2.2. DC Applications and their voltage levels (Hashem et al., 2018)

Application	DC Volt
Wall sockets	12/24 V
Coffee maker, Refrigerator, LED lighting	12 V
Washing machine, Air Conditioner	48 V
PVs connected in DC bus	380 V
Bus way distribution system, Charger	380 V

However, some deficiencies such as power imbalance between power sources and loads, voltage fluctuations due to intermittent Renewable Energy Sources, bus voltage oscillations due to nonlinear load characteristics, interruptions because of load or source faults can lead to voltage instability problem on DC Microgrid.

2.2. ELECTRIC SPRINGS

Electric Spring (ES) is an emerging voltage stabilizing technology to regulate local voltage in power grid for Demand Side Management (DSM). Electric spring can support voltage level, reduce storage capacity and compensate voltage fluctuations (Lee et al., 2013a). The earliest form of ES is used in AC grids and controls the power consumption of Non-Critical Load (NCL) to maintain stable voltage at Point of Common Coupling (PCC). This type of power balancing technology reduces energy storage requirement. By the decrease of battery storage, ES procures other advantageous such as active and reactive power compensation, power factor correction and three phase load balancing in AC mains (Wang et al., 2016a).

Voltage regulation of power grid cannot be maintained stable with high penetration of RESs (Lee et al., 2013b). Dynamically changing power sources like PVs and wind turbines can cause voltage stability problems on power grids (Yang et al., 2017). Power balance between generation and consumption must be matched. Because of ambient conditions, it is hard to estimate power generation of RESs. Modern electronic loads like diode rectifiers can cause voltage harmonics on power grid. Therefore, bus voltage cannot be sustained stable due to intermittency of RESs and voltage quality cannot be maintained.

Three types of AC Electric Spring (AC-ES) is used in studies shown with Figure 2.3(a), Figure 2.3(b) and Figure 2.3(c) (Hashem et al., 2018). In the first type, ES-I provides reactive power compensation and regulate bus voltage. In type ES-II, a battery bank is used instead of capacitor. Thus, ES-II can supply active and reactive power compensation. Series connection of NCL and ES which is named as smart load configuration can be used to regulate bus voltage on PCC and other Critical Loads (CLs). In the third type, ES-III, bi-directional converter is used without Non-Critical Load (NCL) and shunt connected to PCC.

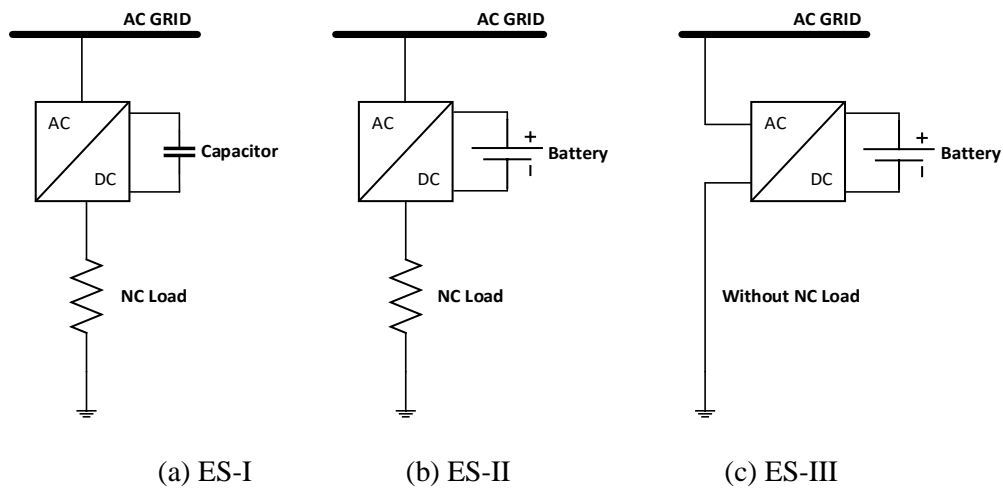
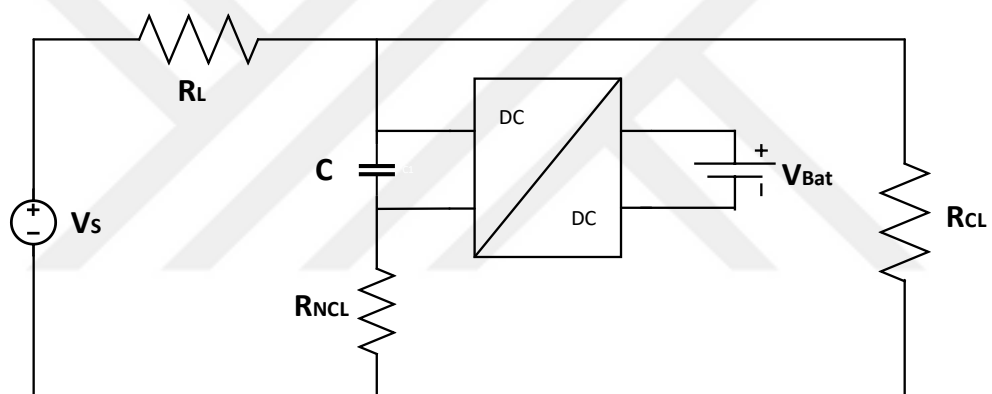


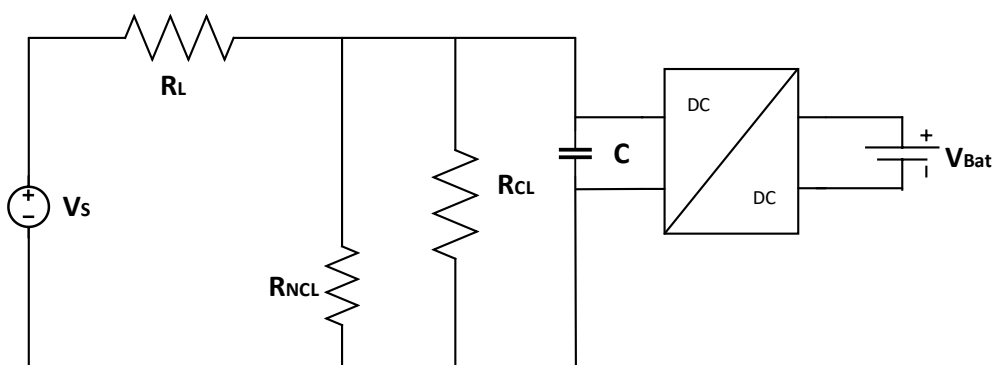
Figure 2.3. Different types of AC-ES (a) ES-I (b) ES-II (c) ES-III

2.3. DC ELECTRIC SPRINGS

DC Electric Spring (DCES) is aimed to remove fluctuations due to intermittency of RESs and maintains stability of DC Microgrid. DC Electric Spring has also other functions such as (i) DC bus voltage regulation, (ii) compensation of double-line frequency harmonics, (iii) fault-ride-through support (Wang et al., 2016a). There are two types of DCES such as series type and shunt type as shown in Figure 2.4(a) and Figure 2.4(b) respectively. Series ES connected in series with NCL in the form of smart load and acts as a controlled voltage source. Shunt ES is directly connected to PCC and does not contain NCL and performs as a controlled current source.



(a)



(b)

Figure 2.4. (a) Series ES and (b) Shunt ES

DC-ES tracks the voltage at PCC. In series type ES, if voltage level on PCC is higher than predefined value, series ES absorbs more amount of current by boosting the NCL voltage. When the voltage level drops, this time PCC voltage is less than reference voltage. Series ES reduces the voltage of NCL to decrease the smart load branch current. Voltage regulation on PCC is carried out by smart load and voltage quality of NCL is sacrificed in order to maintain stable voltage to CL. In shunt type ES, if voltage level is increased by voltage source, the current is absorbed by shunt ES at PCC directly. And vice versa, voltage level is reduced by voltage source, then current is injected to bus. Table 2.3 shows the comparison of Series ES and Shunt ES.

The main advantage of series ES over traditional distributed energy storage system is that required energy capacity for demand side management can be reduced satisfactorily. Because series ES can (i) control the consumed power on NCL and (ii) manipulates the voltage level of energy storage on DC-ES (Mok et al., 2016). On the other hand, shunt ES can response voltage fluctuations faster than series type.

Table 2.3. Comparison of series type ES and shunt type ES

Series ES	Shunt ES
✓ Slower response	✓ Faster dynamic performance
✓ More energy consumption	✓ Less energy consumption
✓ Less energy storage capacity	✓ More energy storage capacity

As shown in Figure 2.4(a) and Figure 2.4(b), DC-ES consists of two parts such as a DC-DC power converter and Energy Storage System (ESS). DC-DC converter has two port. One side is ES port and the second one is battery port. ES port is connected in series with NCL in series type ES. In shunt type ES, ES port is connected to bus directly. ES tracks the voltage on PCC and generates required

voltage level and polarity thus adjusts NCLs power consumption to compensate voltage fluctuations occurred on demand side.

Different types of DC-DC converters are used in various studies. A DCES consisted of a bidirectional paralleled Buck-Boost Converters (BBCs), a Bidirectional Phase-shift full-bridge converter (PSFBC) and an H-Bridge circuit is presented in (Wang et al., 2016b). BBC can operate in voltage boosting and bucking modes in bidirectional. In both modes, BBC cannot change the polarity of its output terminal. In ES theory, when RES generates more than needed, it should be consumed on NCL and vice versa. For this reason, H-Bridge circuit is used to reverse polarity. PSFBC controls the voltages and capacities of batteries and charging conditions to prevent over-charging or over-discharging of batteries.

DCES consisted of DC-DC three port converter (TPC) and Energy Storage System (ESS) is proposed in (Wang et al., 2019b). DC-DC TPC including a high frequency transformer with a full-bridge is located in each port. Input port of TPC is supplied by RES, and NCL and CL locate other two ports separately. ESS is paralleled through bi-directional buck-boost converter with CL.

Full-bridge converter is used to supply power to ES from battery bank in (Wang et al., 2019a). Series ES is connected series with NCL in smart load form. Series ES is a distributed on-site voltage stabilization technology.

Shunt connected DCES is presented in (Gawande et al., 2020). To remove the deviations by injection of RES into power grid, full-bridge DC-DC converter is preferred. Full-bridge DC-DC converter supplies unipolar voltage output and fulfil bidirectional power requirement of shunt DCES.

Since the voltage boost or suppress by DCES is controlled by switching DC-DC converter, the DCES consists of full-bridge, energy storage and low pass filter is presented in (Chen et al., 2020).

Circuit topologies of DCES are compared in (Wang et al., 2021). For series ES, it requires bipolar output voltage and bidirectional power flow. In shunt type DCES, unipolar voltage output and bidirectional power flow are required.

2.4. DC-DC CONVERTERS

DC-DC power converter is an electronic circuit that converts the DC power from one voltage level to another. The interconnection of distributed generations (DGs), DC power grids and DC loads require to match in a common voltage level DC bus. To matchup in a common voltage level some of the components need to step-up their voltage levels while the others step-down. Thanks to rapid advances in semiconductor technology and power electronic devices, DC-DC converters can change the voltage level easily together with very efficient way. There are many types of DC-DC converter such as Buck Converter, Boost Converter, Buck-Boost Converter, Half-Bridge Converter, Full-Bridge Converter etc. (Rashid, 2017).

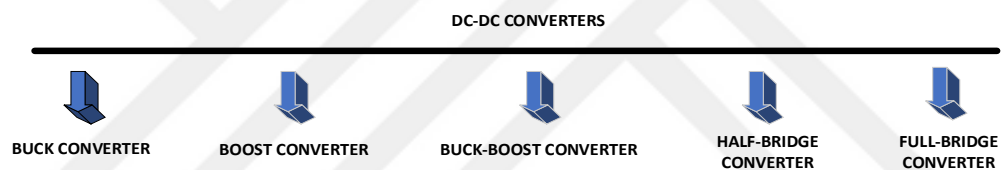


Figure 2.5. The most common types of DC-DC Converters

2.4.1. Buck Converter

The step-down DC-DC converter, generally known as Buck Converter feeds the load which is connected its output terminal with less voltage level than its input voltage. It consists of a DC input voltage source V_S , switch S, diode D, filter inductor L, filter capacitor C and load resistance R. The circuit diagram of Buck Converter is shown in Figure 2.6.

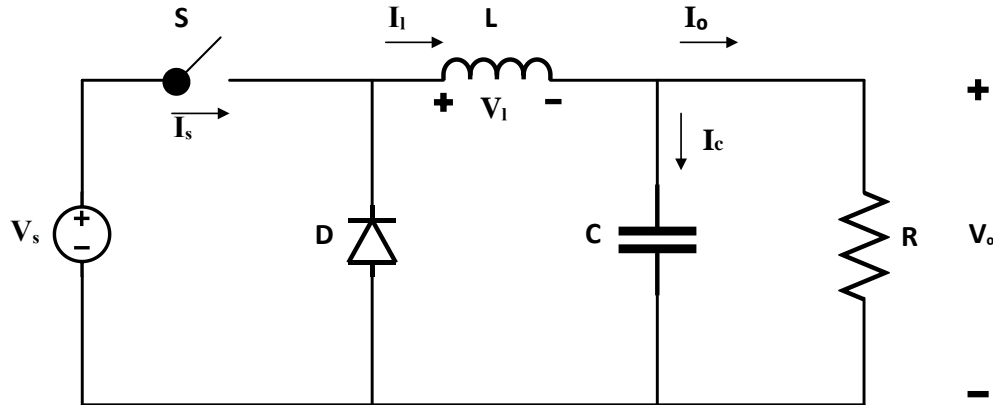


Figure 2.6. Circuit diagram of Buck Converter

The relationship between input voltage and output voltage is shown in Equation 2.1.

$$(V_s - V_o)DT = -V_o(1 - D)T \quad (2.1)$$

Where D is the duty ratio and T is the period. DC voltage transfer function, defined as ratio of output voltage to input voltage,

$$D = \frac{V_o}{V_s} \quad (2.2)$$

Equation 2.3 shows the filter inductance,

$$L = \frac{(1 - D)R}{2f} \quad (2.3)$$

Filter capacitance C must be greater than,

$$C \geq \frac{1 - D}{8L \left(\frac{\Delta V_0}{V_0}\right) f^2} \quad (2.4)$$

2.4.2. Boost Converter

PWM boost converter steps up the input voltage level to its output. It is consisted of an input voltage source V_s , boost inductor L , controllable switch S , diode D , filter capacitor C , and load R . When the switch S is ON state, the current in the inductor increases and diode D is OFF. When the switch S is turned OFF, energy stored in inductor releases to RC circuit through the diode. The circuit diagram of Boost Converter is shown by Figure 2.7.

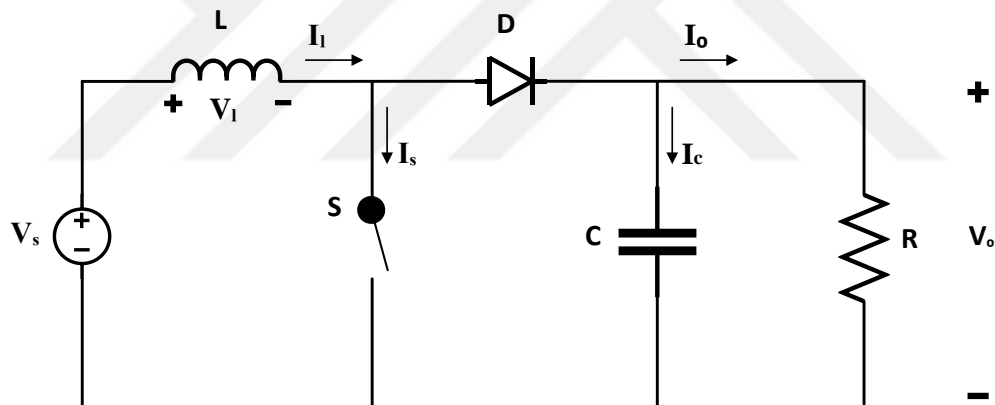


Figure 2.7. Circuit diagram of Boost Converter

Using Faraday's law in boost inductor, we can get,

$$V_s D T = (V_0 - V_s)(1 - D)T \quad (2.5)$$

And DC voltage transfer function,

$$\frac{V_0}{V_S} = \frac{1}{1 - D} \quad (2.6)$$

As the name of converter suggest, the output voltage of converter is always greater than its input voltage. For $L > L_b$, filtering element can be chosen by,

$$L_b = \frac{(1 - D)^2 DR}{2f} \quad (2.7)$$

The minimum value of filter capacitor can be calculated,

$$C \geq \frac{DV_0}{V_r R f} \quad (2.8)$$

2.4.3. Buck-Boost Converter

Transformerless topology of buck-boost converter is shown in Figure 2.8. Converter circuit consists of an input voltage source V_S , controlled switch S, inductor L, diode D, filter capacitor C and load resistance R. When the switch S in ON state, inductor current increased and diode is OFF. When turned OFF, diode D conducts current from output side. The relationship between input and output can be expressed with Equation 2.9,

$$V_S D T = -V_0 (1 - D) T \quad (2.9)$$

Hence voltage transfer function is calculated as Equation 2.10,

$$\frac{V_0}{V_s} = -\frac{D}{1-D} \quad (2.10)$$

The output voltage polarity is negative. Output voltage level can be greater or lower than input by controlling D . If $D = 0.5$ input and output voltage levels are equal.

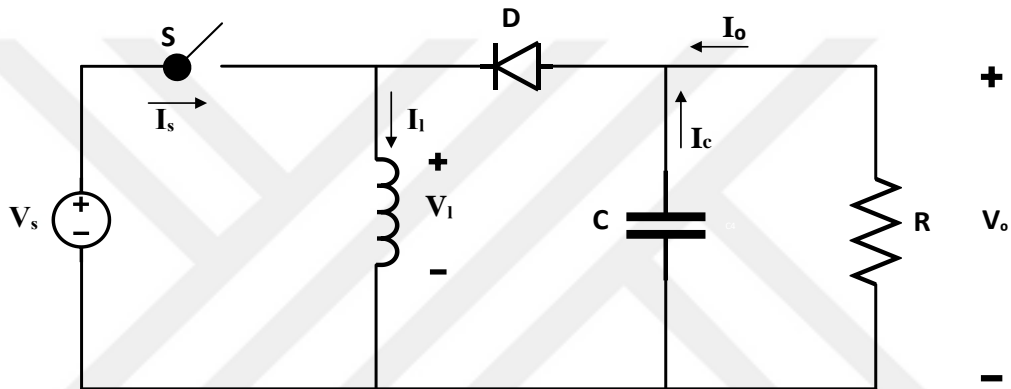


Figure 2.8. Circuit diagram of Buck-Boost Converter

The value of inductor can be calculated by Equation 2.11,

$$L_b = \frac{(1-D)^2 R}{2f} \quad (2.11)$$

And filtering capacitor value is shown with Equation 2.12,

$$C \geq \frac{DV_0}{V_r R f} \quad (2.12)$$

The output side of Buck-Boost Converter is similar to Boost converters output except their polarities.

Half-bridge and Full-bridge converters are preferred in DCES studies thanks to advantageous of bipolar voltage output. In series DCES concept, to control the power consumption of NCL and smart load branch, polarity of ES can be changed (Wang et al., 2021).

2.4.4. Half-Bridge Converter

The circuit diagram of DC-DC Half-Bridge converters shown in Figure 2.9. Switches S1 and S2 operate shifted. When switch S1 is ON, diode D1 conducts and diode D2 is OFF. Diode states change when S2 is ON. The primary of transformer is simplified by adding two voltage sharing input capacitors. The voltage transfer function of Half-Bridge DC-DC converter is shown in Equation 2.13.

$$\frac{V_0}{V_S} = \frac{D}{n} \quad (2.13)$$

Where $D \leq 0.5$. Equations 2.14 and 2.15 can be applied for filtering components calculation.

$$L_b = \frac{(1 - 2D) R}{4f} \quad (2.14)$$

$$C \geq \frac{(1 - 2D)V_0}{32V_r L f^2} \quad (2.15)$$

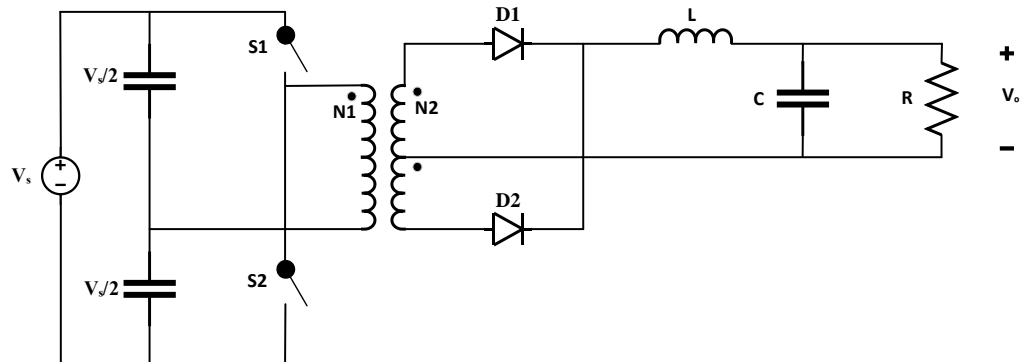


Figure 2.9. Circuit diagram of Half Bridge Converter

2.4.5. Full-Bridge Converter

Input capacitors of Half-Bridge converter are replaced by two controllable switches as seen in Figure 2.10. S_1 and S_4 switching synchronously and when they are ON state, V_S is applied to primary of transformer winding and D_1 conducts. When switches S_2 and S_3 are ON, $-V_S$ is applied to primary of transformer and D_2 conducts. If all switches are OFF, both diodes conduct like push-pull and half-bridge converter. DC transfer function of Full-Bridge converter is,

$$\frac{V_0}{V_S} = \frac{2D}{n} \quad (2.16)$$

where $D \leq 0.5$. Filter components can be obtained by calculating from Equations 2.14 and 2.15.

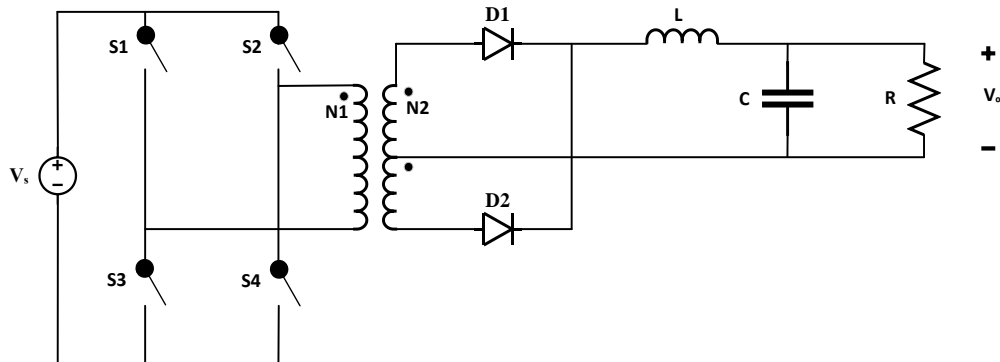


Figure 2.10. Circuit diagram of Full Bridge Converter

2.5. Z-SOURCE CONVERTERS

Input source of converters can be either voltage source or current source just like traditional converters fed by voltage source or current source. However, these traditional converters have some problems. Voltage-fed converters have shoot-through problems, inapplicable for inductive loads and has limited output voltage gain and so current-fed converters have open circuit problem, inapplicable for capacitive loads and limited output current gain. In order to solve these problems Z-Source Converter is proposed (Zhang et al., 2018). Compared to existing DC-DC converters, Z-Source converter can reduce inrush and harmonic currents; provide larger output voltage gain and improve reliability (Fang, 2008). It can also operate in voltage-fed and current-fed conditions and can be perform buck and boost functions.

Converter topology of Z-Source DC-DC converter is shown in Figure 2.11. If input supply of Z-Source DC-DC converter is DC voltage source it works as voltage-fed and shown in Figure 2.12(a). When it is fed by current source, it works as current-fed Z-Source DC-DC converter and shown by Figure 2.12(b). Its current-fed or voltage-fed status can be organized by only two power switches.

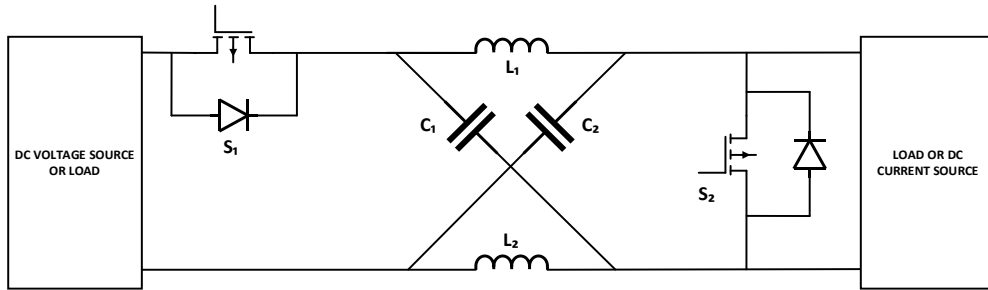


Figure 2.11. Z-Source DC-DC Converter topology

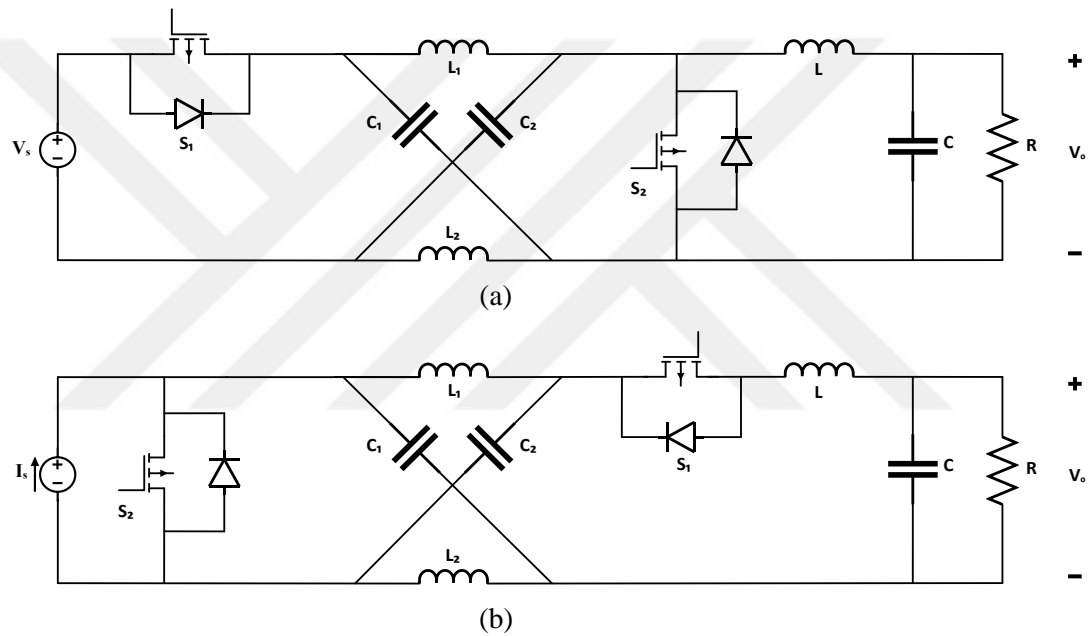


Figure 2.12. Two operating modes of Z-Source DC-DC Converters (a) Voltage-fed (b) Current-fed

Z-Source network consists of two capacitors and two inductors in X-shaped like a bridge between input source and output load.

As the other conventional DC-DC converters, Z-Source DC-DC converter operates with PWM duty ratio control. For the voltage-fed operating mode, active part of switch S2 and diode of S1 switch are turned ON and OFF in complement. In the same way, current-fed operating mode, active part of switch S1 and diode of

switch S2 are turned ON and OFF and power flow is reversed. In these two circumstances, voltage gain between input and output can be controlled by duty ratio D. Voltage transfer ratio, which is controlled by duty ratio D, for voltage-fed and current-fed are shown in Table 2.4.

Table 2.4. Voltage Transfer Ratio of Z-Source DC-DC Converter

Z-Source DC-DC Converter	Voltage Gain
Voltage-fed Mode	$\frac{1-D}{1-2D}$
Current-fed Mode	$\frac{2D-1}{D}$

Z-Source DC-DC converter has a symmetrical topology. That means, L_1 and L_2 inductors and C_1 and C_2 capacitors have same inductance and capacitance values respectively.

$$V_{C1} = V_{C2} = V_C \text{ and } v_{L1} = v_{L2} = v_L \quad (2.17)$$

As an example, voltage-fed Z-Source DC-DC converter is analyzed. In state1, switch S1 is turned ON and switch S2 is turned OFF as shown in Fig 2.13(a). DC voltage source charges the capacitors C1 and C2, while inductors L1 and L2 discharging their energy to load. This occurs in $(1-D)T$ time interval and duty ratio D belongs to switch S2.

$$V_C = V_S - v_L, \quad V_0 = V_S - 2v_L \quad (2.18)$$

In state2, switch S2 is ON and switch S1 is OFF as shown in Fig 2.13(b). Capacitors C1 and C2 are discharged and inductors L1 and L2 are charged and store energy.

$$V_C = v_L, \quad V_0 = 0 \quad (2.19)$$

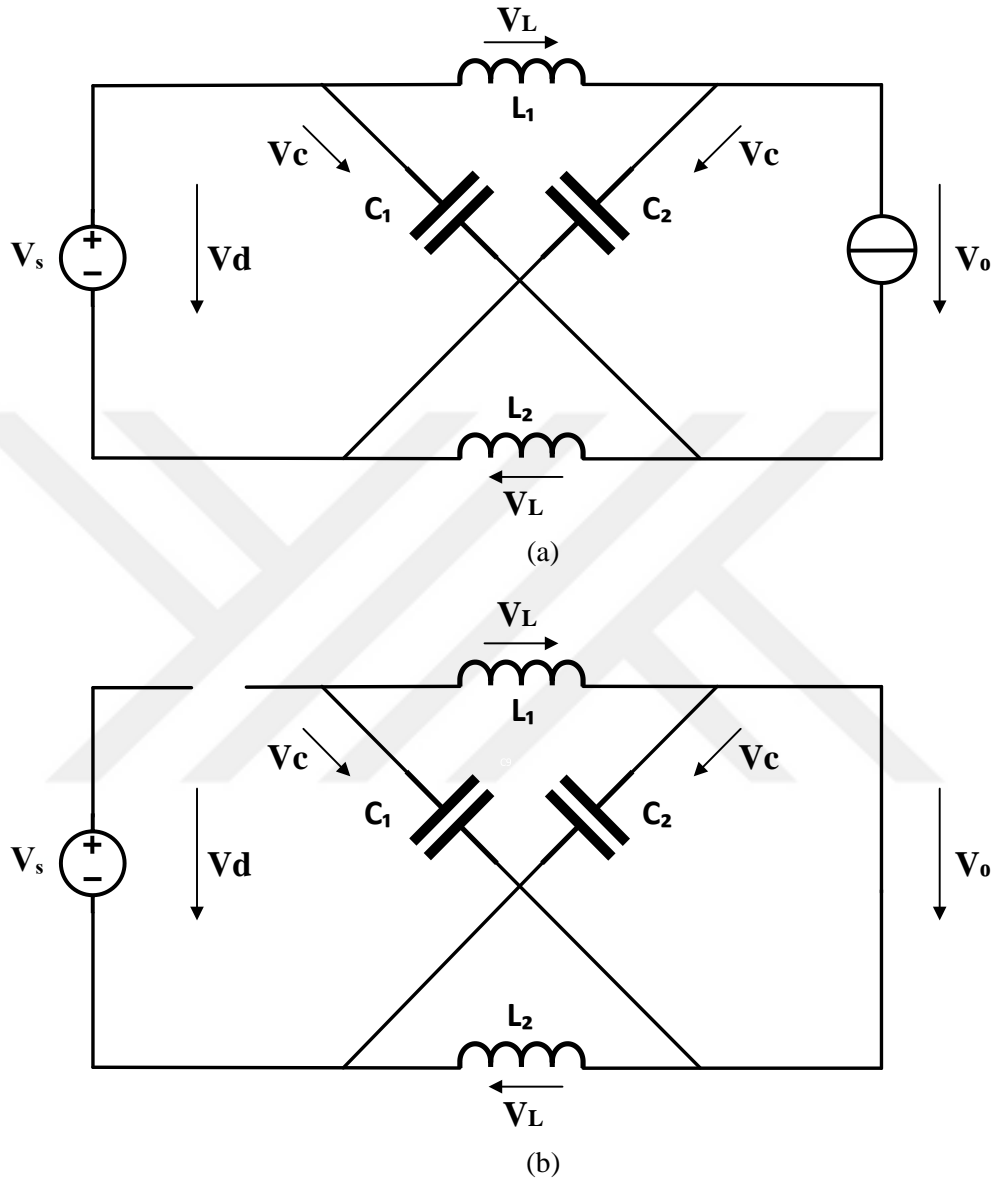


Figure 2.13. (a) State1: S_1 is ON, S_2 is OFF (b) State2: S_1 is OFF, S_2 is ON

The average voltage on inductors as shown in Equation 2.20,

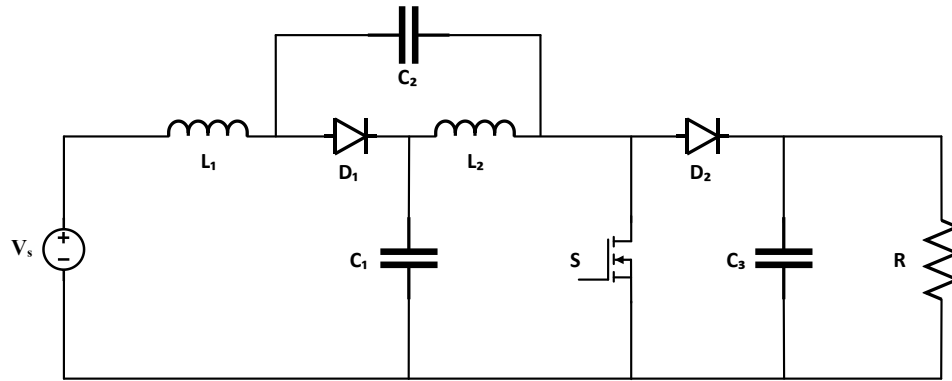
$$\frac{V_C}{V_S} = \frac{1 - D}{1 - 2D} \quad (2.20)$$

And voltage transfer ratio between input and output voltage is expressed as Equation 2.21,

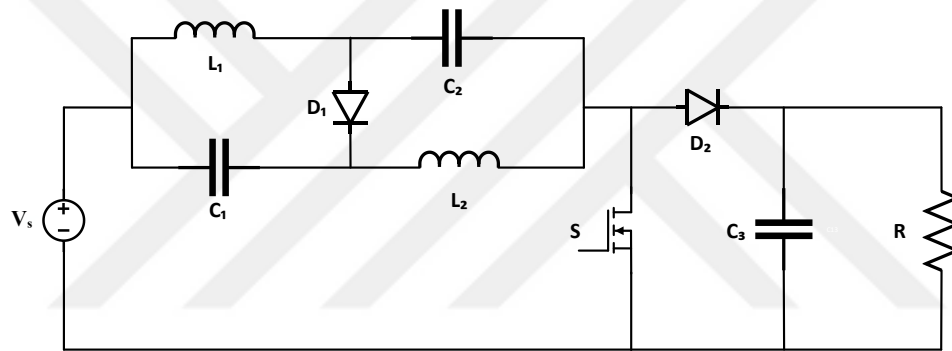
$$\frac{V_0}{V_S} = \frac{1 - D}{1 - 2D} \quad (2.21)$$

As shown with Equation 2.21, output voltage of Z-Source DC-DC converter can be bucked or boosted by controlling duty ratio D .

Z-source DC-DC converter has many advantages over traditional DC-DC converters. But the weaknesses of conventional Z-Source DC-DC converter are large inrush starting current, discrete input current and high voltage stress on capacitors. To overcome this problems, Quasi-Z-Source DC-DC converter is proposed (Cao and Peng, 2009). Quasi-Z-Source DC-DC converter offers continuous input current and decreases voltage stress on capacitor (Shen et al., 2016). There are two types of Quasi-Z-Source DC-DC converter which are continuous current Quasi-Z-Source DC-DC converter and discontinuous current Quasi-Z-Source DC-DC converter shown in Figure 2.14(a) and Figure 2.14(b) respectively.



(a)



(b)

Figure 2.14. Quasi-Z-Source converter (a) Continuous current (b) Discontinuous current

Quasi Z-Source Converter (QZSC) has all advantages of traditional Z-Source Converter. Moreover, on Continuous-Current Quasi Z-Source DC-DC Converter (CQZSC) shown in Fig 2.14(a), C_2 has lower DC voltage on it and thanks to input inductor L_1 it is not required input capacitor. For the Discontinuous-Current Quasi Z-Source DC-DC Converter (DQZSC) shown in Fig 2.14(b), although discontinuous input current, it has lower dc voltage on capacitors C_1 and C_2 .

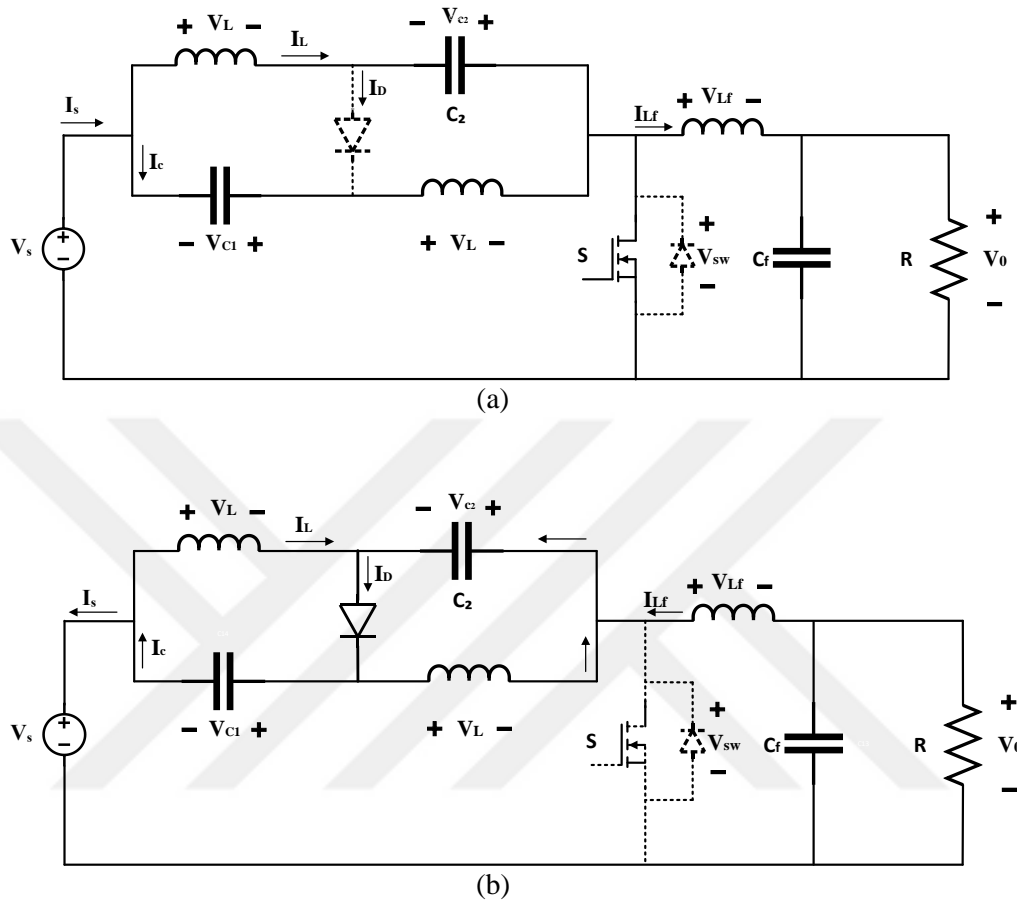


Figure 2.15. Circuit Diagram of Quasi Z-Source (a) S is ON state (b) S is OFF state

For Discontinuous-Current Quasi Z-Source DC-DC Converter, when switch S is ON and diode D is OFF as shown in Fig 2.15(a),

$$v_L = V_S + V_C, \tag{2.22}$$

$$v_{Lf} = -V_0$$

When switch S is OFF and diode D is ON, shown with Fig 2.15(b),

$$v_L = -V_C, \tag{2.23}$$

$$v_{Lf} = v_s - V_0 = V_S + 2V_C - V_0$$

Equation 2.24 can be derived from Equation 2.22 and Equation 2.23,

$$(V_S + V_C)d + (-V_C)(1 - d) = 0 \rightarrow V_C = \left(\frac{d}{1-d}\right)V_S \quad (2.24)$$

$$(-V_0)d + (V_S + 2V_C - V_0)(1 - d) = 0 \quad (2.25)$$

$$\frac{V_0}{V_S} = \frac{1-d}{1-2d} \quad (2.26)$$

Compared to traditional Z-Source DC-DC Converter, Quasi Z-Source DC-DC Converters provide reduced passive component ratings, less component count and improved input profiles (Anderson and Peng, 2008)



3. POWER CIRCUIT MODELING

With the widespread of Distributed Generation (DG) and Renewable Energy Sources (RES) in power systems, Microgrid concept has becoming more popular. For distributed generation and local loads, Microgrids are more effective and efficient way.

Compared to AC power grids, DC power grids have higher efficiency thanks to fewer conversion steps. In addition to this, DC systems have not required frequency synchronization and reactive power regulation. Contrary to AC power systems frequency synchronization, DC power systems only require voltage control. While AC systems are advantageous for ease of voltage transformation, DC systems are preferred to increased efficiency by integration of renewable energy sources, storage equipment and DC loads.

By the recent advancement in power electronic devices, DC Microgrids are more and more attractive. DC systems offer higher reliability and efficiency, simpler control and natural interface between DC renewable generation, energy storages and modern electronic loads.

Although DC Microgrids do not required synchronization and frequency problems, it still needs to ensure power balance between sources and sinks. Due to the intermittency of Renewable Energy Sources and load changes, some voltage quality problems and power imbalances can occur. Traditionally, these problems are mitigated by energy storages. But it is needed more storage capacity and it means higher investment and maintenance cost.

To overcome this instantaneous voltage fluctuation between sources and loads, a demand side voltage stabilization system named as Electric Spring (ES) is proposed. AC Electric Springs (AC-ESs) are used for AC systems to provide power balance between sources and loads at the instantaneous load or supply changes. By wide spreading of DC Microgrids, Electric Spring is applied to DC grids.

The most common voltage quality problem in DC Microgrid, power imbalance between sources and sinks can be easily compensated by using DC Electric Spring (DCES). DCES is a power suspension system to remove instantaneous voltage fluctuations due to intermittent renewable energy sources or load changes on demand side to procure voltage quality.

DC Electric Spring has a limited voltage compensation range. It can both suppress and boosts the voltage level by tracking voltage level on Critical Load. The output of DC Electric Spring can be positive or negative according to desired value of DC link and Critical Load voltage. To maintain stable voltage on Critical load, Non-Critical Load voltage can be sacrificed.

In this thesis, a DCES is modeled to supply stable and reliable power to Critical Load. DCES is consisted of a DCES port, a DC-DC converter unit and battery group. To supply the required voltage to ES port, bipolar output DC-DC converter is needed. Half-bridge DC-DC converter is preferred to ease of control, less number of switching device and bipolar output voltage. As known to all, storage equipment is the most expensive part of these type of circuits. To reduce the number of battery and still supply the required level voltage, Z-Source bidirectional DC-DC converter is integrated to Half-Bridge DC-DC converter and a new DC-DC converter configuration is proposed. By the advantage of Z-Source DC-DC converter, up to ten times battery voltage level can be provided to ES terminals.

The proposed system is composed of PV modules, DC link, Half-Bridge DC-DC Converter, Z-Source DC-DC Converter, battery bank, Critical and Non-Critical loads as shown in Fig (3.1).

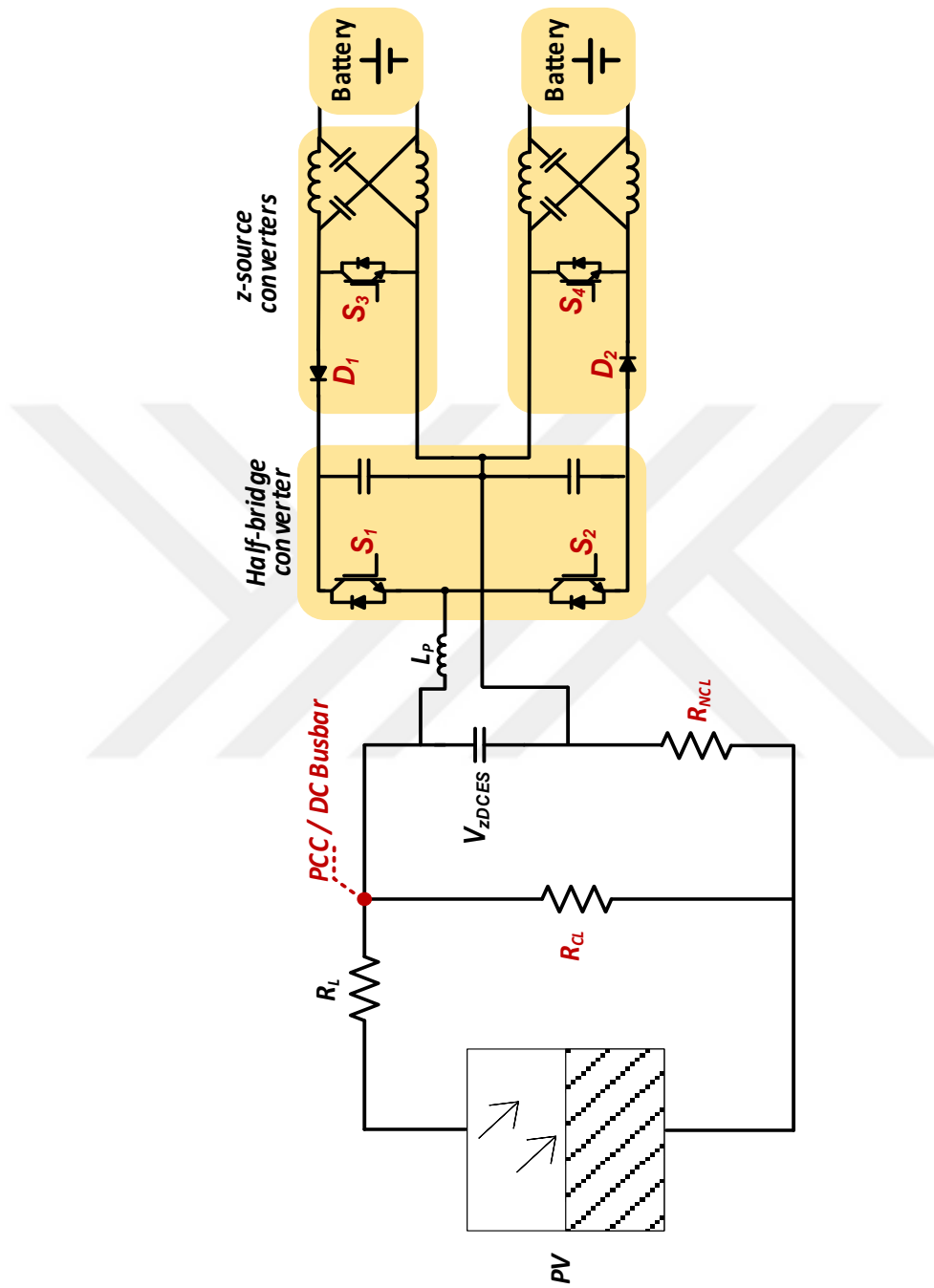


Figure 3.1. Power Circuit Model of The Proposed System

3.1. Power Circuit Modeling of DC Electric Spring (DCES)

This study presents an electric active power suspension technology for voltage stabilization known as DC Electric Spring (DCES). The proposed DCES is connected series with Non-Critical Load as shown with Fig (3.1.) When a fluctuation occurs in supply side, DCES can adjust suitable ES voltage in such a way that controlling the NCL power consumption and changing the polarity of ES port voltage.

$$\begin{aligned} V_{bus} &= V_{ES} + V_0 \\ &= V_{ES} + I_{sl}R_0 \end{aligned} \quad (3.1)$$

Where V_{ES} is electric spring voltage, V_0 is NCL voltage, R_0 is load resistance of NCL and I_{sl} is smart load current. And ES power P_{ES} , NCL power P_0 and smart load power P_{sl} can be calculated as follows,

$$P_{ES} = V_{ES} \cdot I_{sl} = \frac{V_{ES} (V_{bus} - V_{ES})}{R_0} \quad (3.2)$$

$$P_0 = V_0 \cdot I_{sl} = \frac{(V_{bus} - V_{ES})^2}{R_0} \quad (3.3)$$

$$P_{sl} = V_{bus} \cdot I_{sl} = \frac{V_{bus}(V_{bus} - V_{ES})}{R_0} \quad (3.4)$$

When DC transmission line resistance taking into consideration, supply side voltage practical operating range can be calculated better. Because ES has a limited compensation range on busbar. Distribution line resistance R_d is taken into

consideration and load side power P_{bus} , smart load power P_{sl} , and critical load power P_C are calculated as,

$$P_C = \frac{V_{bus}^2}{R_C} \quad (3.5)$$

$$P_{bus} = V_{bus} \cdot I_{bus} = P_{sl} + P_C \quad (3.6)$$

Thus, supply side voltage is,

$$V_{DC} = V_{bus} + R_d I_s = V_{bus} + \frac{R_d}{V_{bus}} (P_{sl} + P_C) \quad (3.7)$$

By using Eq (3.4) and Eq (3.7) supply side voltage expressed as,

$$V_{DC} = V_{bus} + \frac{R_d}{V_{bus}} \left(\frac{V_{bus}(V_{bus} - V_{ES})}{R_0} + P_C \right) \quad (3.8)$$

From Eq (3.8); $V_{DC}=V_{DC_{min}}$ when $V_{ES}=V_{ES_{max}}$ and $V_{DC}=V_{DC_{max}}$ when $V_{ES}=V_{ES_{min}}$;

$$V_{DC_{min}} = V_{bus} + \frac{R_d}{V_{bus}} \left(\frac{V_{bus}(V_{bus} - V_{ES_{max}})}{R_0} + P_C \right) \quad (3.9)$$

$$V_{DC_{max}} = V_{bus} + \frac{R_d}{V_{bus}} \left(\frac{V_{bus}(V_{bus} - V_{ES_{min}})}{R_0} + P_C \right) \quad (3.10)$$

$$V_{bus} = f_1 (R_d, R_C, R_0, V_{ES}, V_{DC})$$

$$= \frac{R_0 R_C}{R_0 R_C + R_C R_d + R_d R_0} \left(V_{DC} + \frac{R_d V_{ES}}{R_0} \right) \quad (3.11)$$

Hence DC bus voltage can be expressed as,

$$V_{bus} = \begin{cases} f_1(R_d, R_C, R_0, V_{ES_min}, V_{DC}) & : V_{DC} < V_{DC_min} \\ V_{bus_ref} & : V_{DC_min} \leq V_{DC} \leq V_{DC_max} \\ f_1(R_d, R_C, R_0, V_{ES_max}, V_{DC}) & : V_{DC} > V_{DC_max} \end{cases}$$

ES voltage changes by V_{DC} can be expressed as,

$$\begin{aligned} V_{ES} &= f_2(R_d, R_C, R_0, V_{bus}, V_{DC}) \\ &= \frac{R_0}{R_d} \left[V_{bus} \left(1 + \frac{R_C R_d + R_d R_0}{R_0 R_C} \right) - V_{DC} \right] \end{aligned} \quad (3.12)$$

Thus, ES voltage can be represented as,

$$V_{ES} = \begin{cases} V_{ES_max} & : V_{DC} < V_{DC_min} \\ f_2(R_d, R_C, R_0, V_{bus_ref}, V_{DC}) & : V_{DC_min} \leq V_{DC} \leq V_{DC_max} \\ V_{ES_min} & : V_{DC} > V_{DC_max} \end{cases}$$

Table 3.1. System Specifications of Experiment

Description	Parameter	Value
Nominal DC Bus Voltage	V_{bus_ref}	48 V
Distribution Line Resistance	R_d	0.37 Ω
Critical Load Resistance	R_C	14.05 Ω
Non-Critical Load Resistance	R_0	12 Ω

Specifications of experiment is shown in Table 3.1. Using these values into Eq 3.9 and Eq 3.10, $V_{DC_min} = 49.26$ V and $V_{DC_max} = 50.91$ V can be evaluated ($V_{bus_ref} = 48$ V).

$$-5.4 \text{ V} \leq V_{ES} \leq 47.7 \text{ V}$$

$$V_{bus} = \begin{cases} f_1(R_d, R_C, R_0, V_{ES_min}, V_{DC}) & : V_{DC} < 49.26 \\ 48 \text{ V} & : 49.26 \text{ V} \leq V_{DC} \leq 50.91 \text{ V} \\ f_1(R_d, R_C, R_0, V_{ES_max}, V_{DC}) & : V_{DC} > 50.91 \text{ V} \end{cases}$$

And,

$$V_{ES} = \begin{cases} 47.7 \text{ V} & : V_{DC} < 49.26 \text{ V} \\ f_2(R_d, R_C, R_0, V_{bus_ref}, V_{DC}) & : 49.26 \text{ V} \leq V_{DC} \leq 50.91 \text{ V} \\ -5.4 \text{ V} & : V_{DC} > 50.91 \text{ V} \end{cases}$$

The proposed circuit is simulated for to verify calculated values. DC power source is adjusted between 49V to 51V.

3.2. Power Circuit Modeling of DC-DC Converter

Integration of Z-Source Converter into a Half-Bridge Converter is modeled in this paper. Half-Bridge converters are able supply both positive and negative output voltage. But sometimes shoot-through can occurs because of series connected switches and switches can damaged from strong current flows. Furthermore, Half-Bridge converter has limited output voltage problem and unbalanced midpoint problems can leads to large ripples on output side. To overcome limited voltage and shoot-through problem, integration of an LC circuit named as Z-Source into Half-Bridge is proposed. By adding Z-Source network into Half-Bridge converter, it can supply bipolar output voltage and can reach higher output voltage than conventional ones.

As shown in Fig 3.2, IGBT/Diode is used as switching equipment and capacitances are connected parallel to IGBTs. Each capacitor has half of battery supply voltage on it. To reduce number of battery and maintain same voltage with less battery, Z-Source converter is added for both upper and lower side.

Designed Z-Source Neutral Point Clamped (NPC) converter operates with minimal number of device commutations per half cycle, maximal voltage boost, lower stress on semiconductor devices and be configured to switch with minimum harmonic distortion (Loh et al., 2006). The Z-Source NPC uses two LC network that are connected to two capacitances. Two LC networks are short-circuited to minimization of harmonic distortion and device commutations per half carrier cycle (Loh et al., 2007).

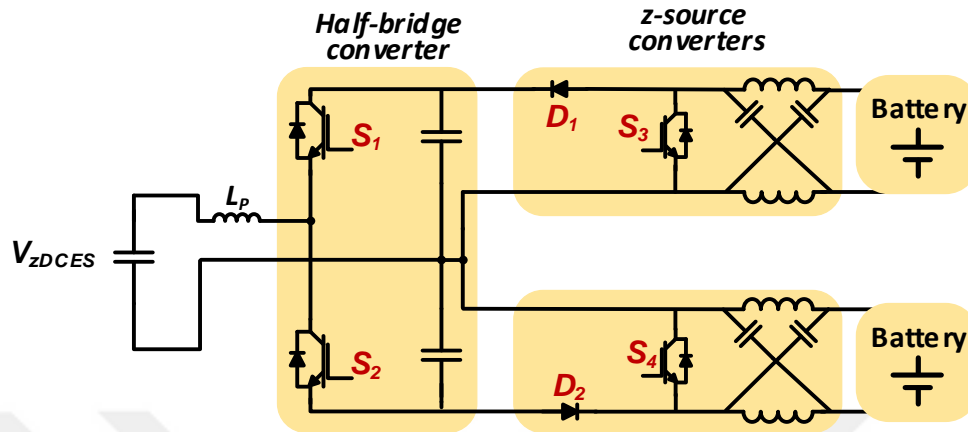


Figure 3.2. Power Circuit Model of Proposed DC-DC Converter

Table 3.2. Parameters of Half-Bridge Converter

Description	Parameter	Value
Switching Device-1	IGBT/Diode1	
Switching Device-2	IGBT/Diode2	
Storage Capacitor-1	C_1	1500 uF
Storage Capacitor-2	C_2	1500 uF
Filter Capacitor	C_0	6.6 uF
Filter Inductor	L_0	600 uH

Voltage-fed Z-Source DC-DC converter is integrated to improve voltage gain as shown in Fig 3.2. Compared to existing DC-DC converters, Z-Source can provide larger gain, reduce inrush current and improve reliability. The Z-Source converters are equivalent for upper and lower side and also circuit parameters are symmetrical.

$$L_{Z1} = L_{Z2} = L_{Z3} = L_{Z4} \text{ and } C_{Z1} = C_{Z2} = C_{Z3} = C_{Z4}$$

Table 3.3. Parameters of Z-Source Converter

Description	Parameter	Value
Z-Source Inductor-1	L_{Z1}	150 uH
Z-Source Inductor-2	L_{Z2}	150 uH
Z-Source Inductor-3	L_{Z3}	150 uH
Z-Source Inductor-4	L_{Z4}	150 uH
Z-Source Capacitor-1	C_{Z1}	45 uF
Z-Source Capacitor-2	C_{Z2}	45 uF
Z-Source Capacitor-3	C_{Z3}	45 uF
Z-Source Capacitor-4	C_{Z4}	45 uF
Battery Voltage	V_{Bat}	24 V

4. CONTROLLER MODELING

The proposed converter generates required voltage level and polarity from batteries and compensates fluctuations occurred by intermittency of renewable energy sources. PWM generator tracks the voltage on critical load and compares with reference value. Difference between reference and set value is treated by controller. Generated controller signal converted to pulse signal to create PWM signal by PWM generator. Half-Bridge and Z-Source converters IGBT/Diodes are triggered by PWM pulse signal “G” as shown in Fig 4.1.

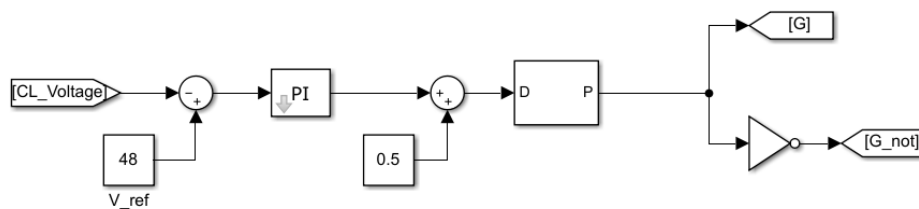


Figure 4.1. Controller Circuit Model of Proposed DC-DC Converter

Critical Load Voltage (CL_voltage) is measured continuously and sum of reference value and CL_voltage is sent to controller. Controllers K_p and K_i gains and controller schematic diagram is shown in Fig 4.2.

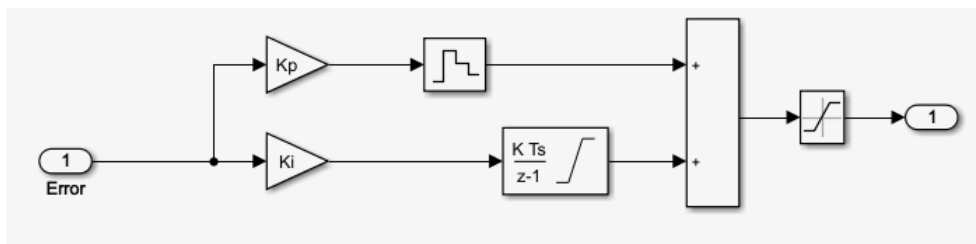


Figure 4.2. Schematic Diagram of PI Controller

Table 4.1. Parameters of PI Controller

Description	Parameter	Value
Proportional Gain	K_p	6
Integral Gain	K_i	0
Upper Limit		0.49
Lower Limit		-0.49

When supply side voltage is its nominal, difference between set value and CL_voltage is almost zero and Half-Bridge Converter must supply zero voltage to its output terminal. While PI Controller generates “0” signal, Half-Bridge need to be triggered by “0.5” duty signal to “0” voltage output. As shown is Fig 4.1, “0.5” constant is added to produce zero voltage by Half-Bridge Converter.

PWM generator model converts the given duty signal into pulse signal “G” for triggering IGBT/Diode switches. “G_not” is the reverse of gate signal “G” and used for both Half-Bridge lower side IGBT/Diode switch.

5. SIMULATION RESULTS

The circuit diagram of proposed system is shown in Figure 5.1. Critical load, Non-Critical load and Power Supply is configured in order to implement any load or supply changes. The whole system is modeled and simulated by using MATLAB/Simulink. Intermittency of PV is simulated by MATLAB/Simulink and power changes on Critical Load (CL) and Non-Critical Load (NCL) are observed. Parameters of proposed system is given in Table 5.1.

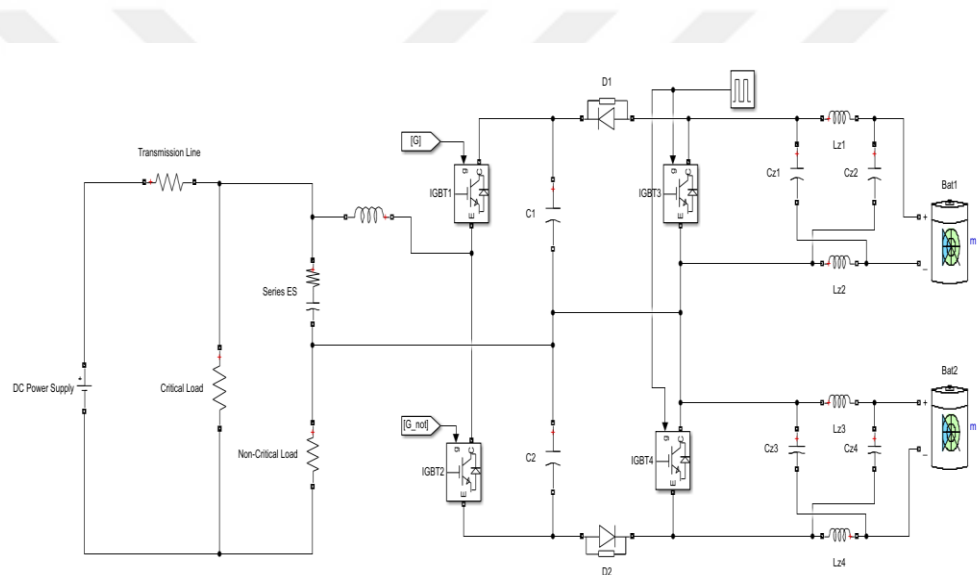


Figure 5.1. Circuit Diagram of Proposed System

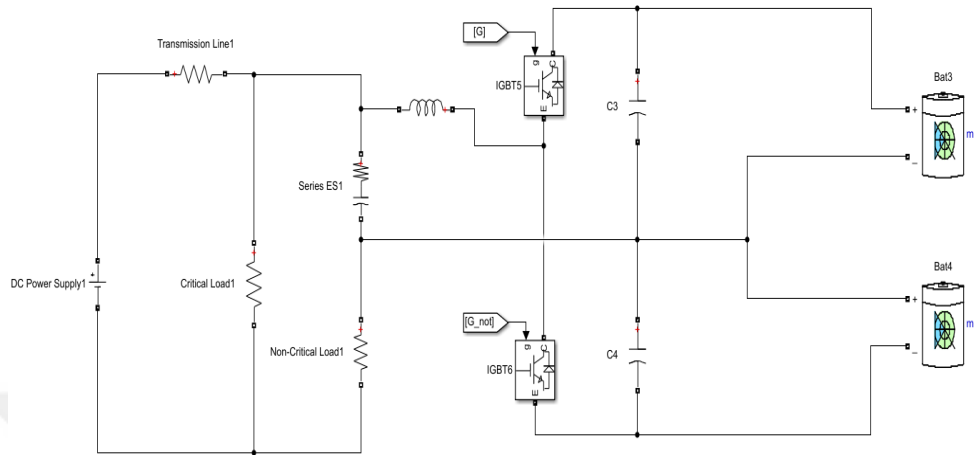


Figure 5.2. Circuit Diagram of Existing Topology (Mok et al., 2016)

Table 5.1. Parameters of Proposed System

Description	Parameter	Value
Nominal DC Bus Voltage	V_{bus_ref}	48 V
Distribution Line Resistance	R_d	0.37 Ω
Critical Load Resistance	R_C	14.05 Ω
Non-Critical Load Resistance	R_0	12 Ω
Switching Device-1	IGBT/Diode1	
Switching Device-2	IGBT/Diode2	
Switching Device-3	IGBT/Diode3	
Switching Device-4	IGBT/Diode4	
Storage Capacitor-1	C_1	1500 μ F
Storage Capacitor-2	C_2	1500 μ F
Filter Capacitor	C_0	6.6 μ F
Filter Inductor	L_0	600 μ H
Z-Source Inductor-1	L_{Z1}	150 μ H
Z-Source Inductor-2	L_{Z2}	150 μ H
Z-Source Inductor-3	L_{Z3}	150 μ H
Z-Source Inductor-4	L_{Z4}	150 μ H
Z-Source Capacitor-1	C_{Z1}	45 μ F
Z-Source Capacitor-2	C_{Z2}	45 μ F
Z-Source Capacitor-3	C_{Z3}	45 μ F
Z-Source Capacitor-4	C_{Z4}	45 μ F
Battery Voltage	V_{Bat}	24 VDC
Switching Frequency	f	20kHz

5.1. Case 1

In this case, voltage level of power supply changes between 49V and 51V. For Critical Load voltage requirement, 48V is referenced. As a Non-Critical Load, a constant resistive load is used. Supply side voltage level, Electric Spring (ES) voltage level, voltage levels of Critical and Non-Critical loads are represented. By changing supply side voltage, behaviors of three different circuits are compared.

In the first circuit, supply side voltage level, ES voltage level, CL voltage level and NCL voltage level of existing topology is shown in Figure 5.3 (Mok et al., 2016). This topology uses DCES as series with NCL. 6 series battery is used for each upper and lower side, this means 72V is supplied from each branch.

In the second circuit shown in Figure 5.4, same circuit occurred by same parameters is driven by same input voltage supply, but DC Electric Spring (DCES) is removed. As shown in Figure 5.4, CL voltage level is directly affected by input voltage changes.

The proposed circuit is run by the same input voltage source. ES voltage, NCL voltage and CL voltage levels are represented in Figure 5.5. Difference from existing topology given with Figure 5.3, to reduce battery bank voltage level Z-Source DC-DC Converter is integrated between battery bank and Half-Bridge DC-DC Converter. By the integration of Z-Source into proposed circuit, battery bank voltage level is reduced to 24V. Thanks to Z-Source converter, lower-level battery voltage can be boosted to required level.

Comparison of three different circuits CL voltage levels is given by Figure 5.6. As shown in graph, CL voltage level is maintained more stable. Number of used equipments and battery voltage levels are given in Table 5.1.

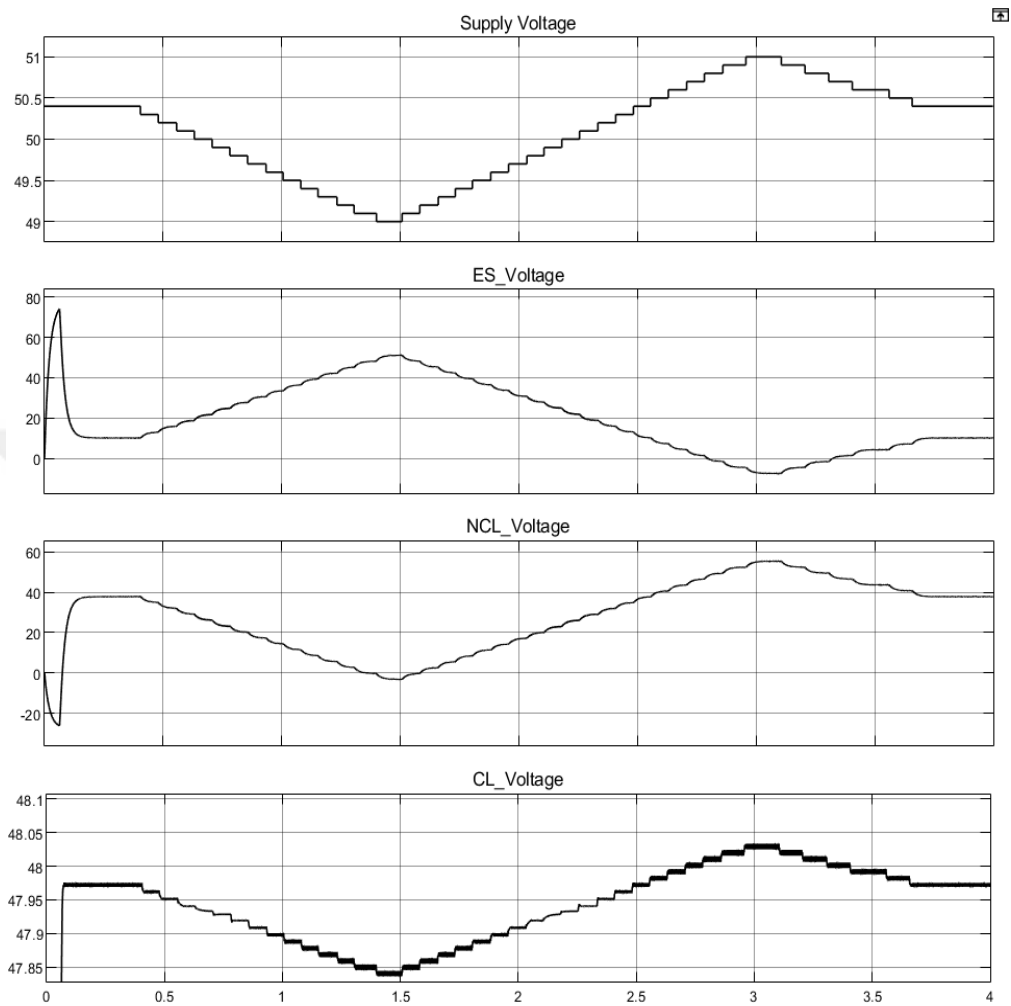


Figure 5.3. Voltage Levels of Existing Topology without Z-Source DC-DC Converter

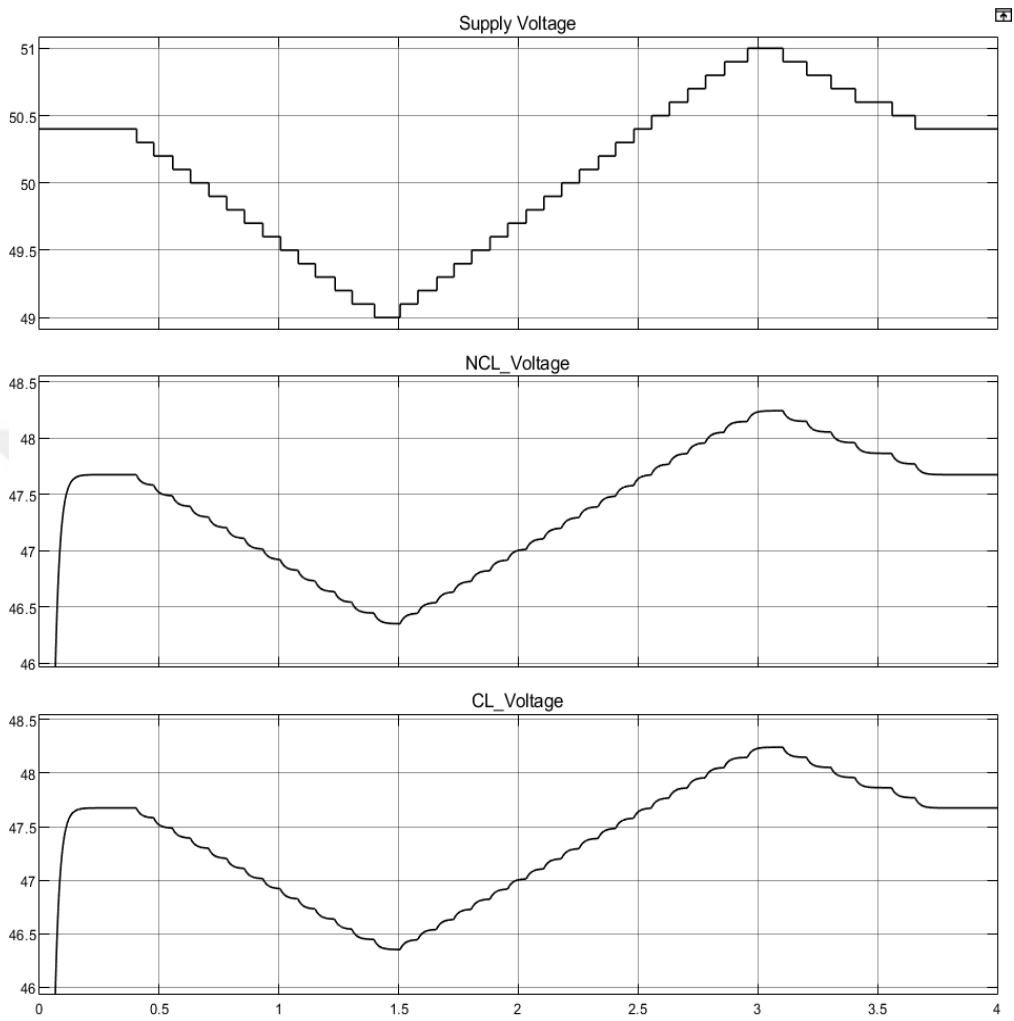


Figure 5.4. Voltage Levels of Loads without DCES

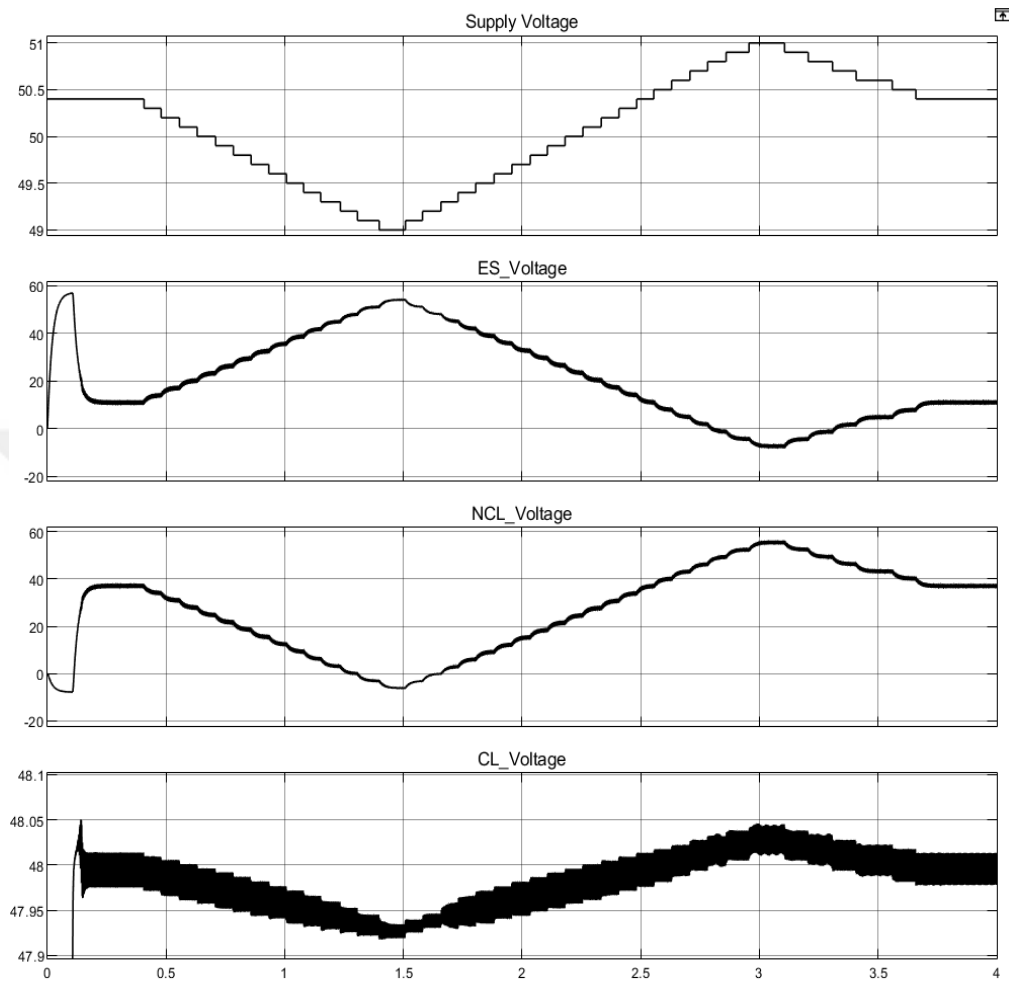


Figure 5.5. Voltage Levels of Proposed Topology

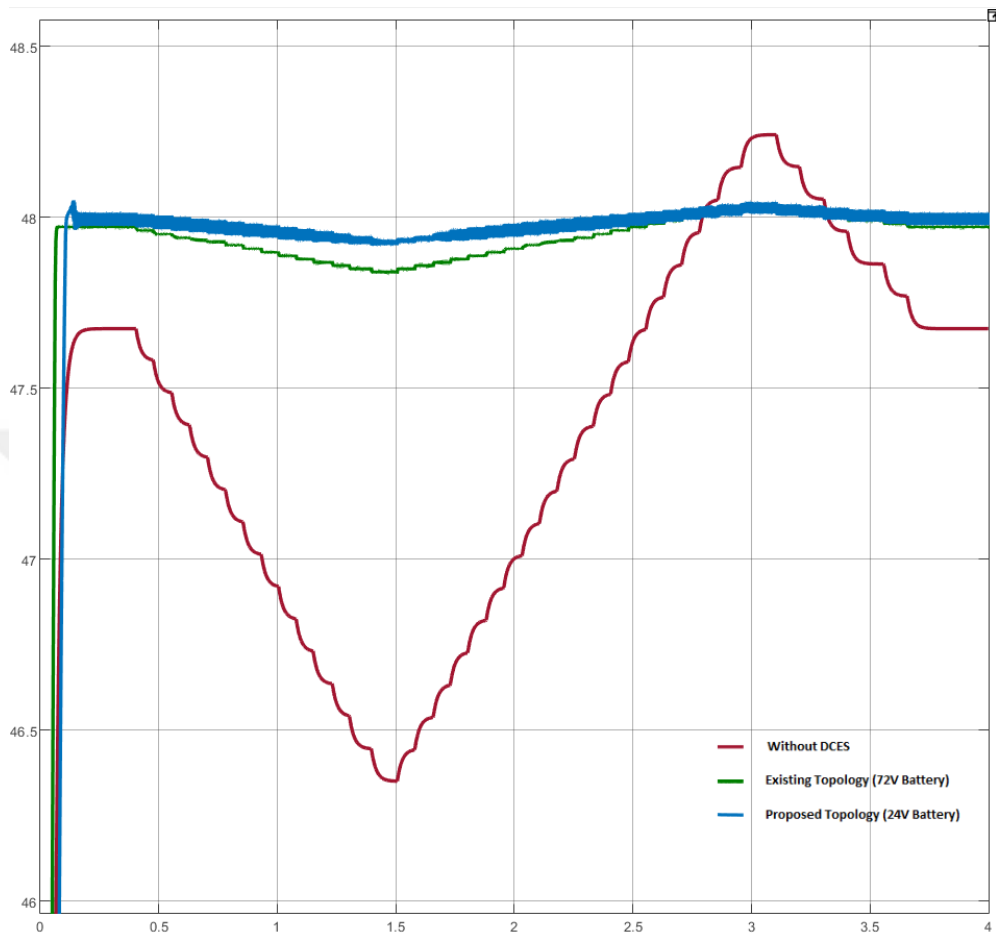


Figure 5.6. Comparison of Voltage Levels of Topologies

Table 5.2. Comparison of Circuit Parameters

	V_{IN}	R_{CL}	R_{NCL}	DCES	IGBT	Passive Elements	V_{Bat}
Existing Topology	49-51V	14,05 Ω	12 Ω	used	2	2 Capacitor	72V
Without DCES	49-51V	14,05 Ω	12 Ω	-	-	-	-
Proposed Topology	49-51V	14,05 Ω	12 Ω	used	4	6 Capacitor 4 Inductor 2 Diode	24V

As shown with figures, the proposed circuit can maintain CL voltage level between acceptable limits. Compared to existing circuit design, using a few parts of switching and passive element more, battery voltage level is reduced 1/3.

Table 5.3. Total Cost of Existing Topology

Circuit Element	Amount Used	Unit Price	Cost
IRFP31N50L MOSFET	2	6,42\$	12,84\$
1500UF 50V CAPACITOR	2	2,04\$	4,08\$
LC-R127R2NA BATTERY (12V-7,2Ah)	24	39,97\$	959,28\$
TOTAL COST			976,20\$

Table 5.4. Total Cost of Proposed Topology

Circuit Element	Amount Used	Unit Price	Cost
IRFP31N50L MOSFET	4	6,42\$	25,68\$
1500UF 50V CAPACITOR	2	2,04\$	4,08\$
TLV12150F4 BATTERY (12V-15Ah)	4	49,99\$	199,96\$
45UF 35VDV CAPACITOR	4	2,17\$	8,68\$
150UH 34A INDUCTOR	4	34,28\$	137,12\$
TOTAL COST			375,52\$

Used switching and passive element and battery bank costs in existing and proposed topologies are calculated in Table 5.3 and Table 5.4 respectively. As shown in tables, the most expensive equipment in circuits is battery bank. Instead of 24 pieces batteries in existing topology, proposed circuit uses 4 batteries. The proposed topologies total cost is about %38 of existing topology.

5.2. Case 2

In the second case, the proposed circuit is run with same parameters as voltage level of power supply changes between 49V and 51V. For Critical Load voltage requirement, 48V is referenced. As a Non-Critical Load, a constant resistive load is used. In this case, it is aimed that how ES behaves when any load changes occur in Non-Critical Load.

In time interval 0-2, supply side voltage level changes between 49-51V with $12\ \Omega$ constant resistive Non-Critical Load and $14,05\ \Omega$ Critical Load.

When time $t=2$, one more $12\ \Omega$ constant resistive Non-Critical Load is implemented parallel with existing Non-Critical Load and also series with ES. Between time interval 2-4, supply side voltage is changed between 49-51V.

Supply side voltage level, Electric Spring (ES) voltage level, voltage levels of Critical Load and Non-Critical load are represented. By changing supply side voltage behaviors of three different circuits are compared with changing load circumstances.

In the first circuit, supply side voltage level, ES voltage level, CL voltage level and NCL voltage level of existing topology is shown in Figure 5.7. This topology uses DCES as series with NCL. 6 series battery is used for each upper and lower side, this means 72V is supplied from each branch. When time $t=2$, one more $12\ \Omega$ NCL is applied as parallel with working NCL and same input voltage between time interval 0-2 is repeated.

In the second circuit shown in Figure 5.8, same circuit occurred by same parameters is driven by same input voltage supply, without DC Electric Spring (DCES). As shown in Figure 5.8, CL voltage level is directly affected by input voltage changes. And time interval 2-4, Critical and Non-Critical Load voltages are lower than time interval 0-2.

The proposed circuit is run by the same input voltage source also. ES voltage, NCL voltage and CL voltage levels are represented in Figure 5.9. Difference from existing topology given with Figure 5.7, to reduce battery bank

voltage level Z-Source DC-DC Converter is integrated between battery bank and Half-Bridge DC-DC Converter. By the integration of Z-Source into proposed circuit, battery bank voltage level is reduced to 24V. Thanks to Z-Source converter, lower-level battery voltage can be boosted to required level.

Comparison of three different circuits CL voltage level is given by Figure 5.10. As shown in graph, DCES maintains stable CL voltage level when any load changes occur in Non-Critical Load. Without DCES, CL voltage is directly affected by supply side voltage changes and in any load changes it is also affected adversely.



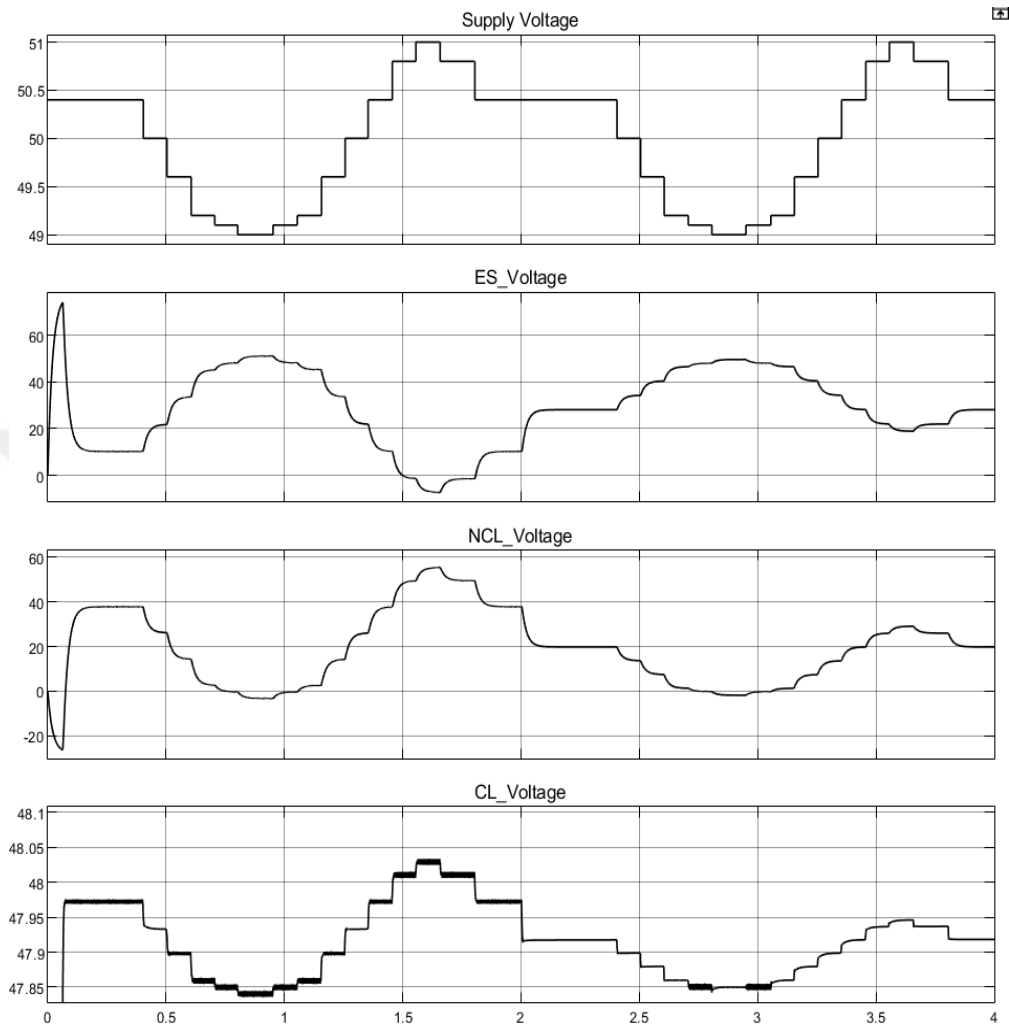


Figure 5.7. Voltage Levels of Existing Topology without Z-Source DC-DC Converter by changing NCL

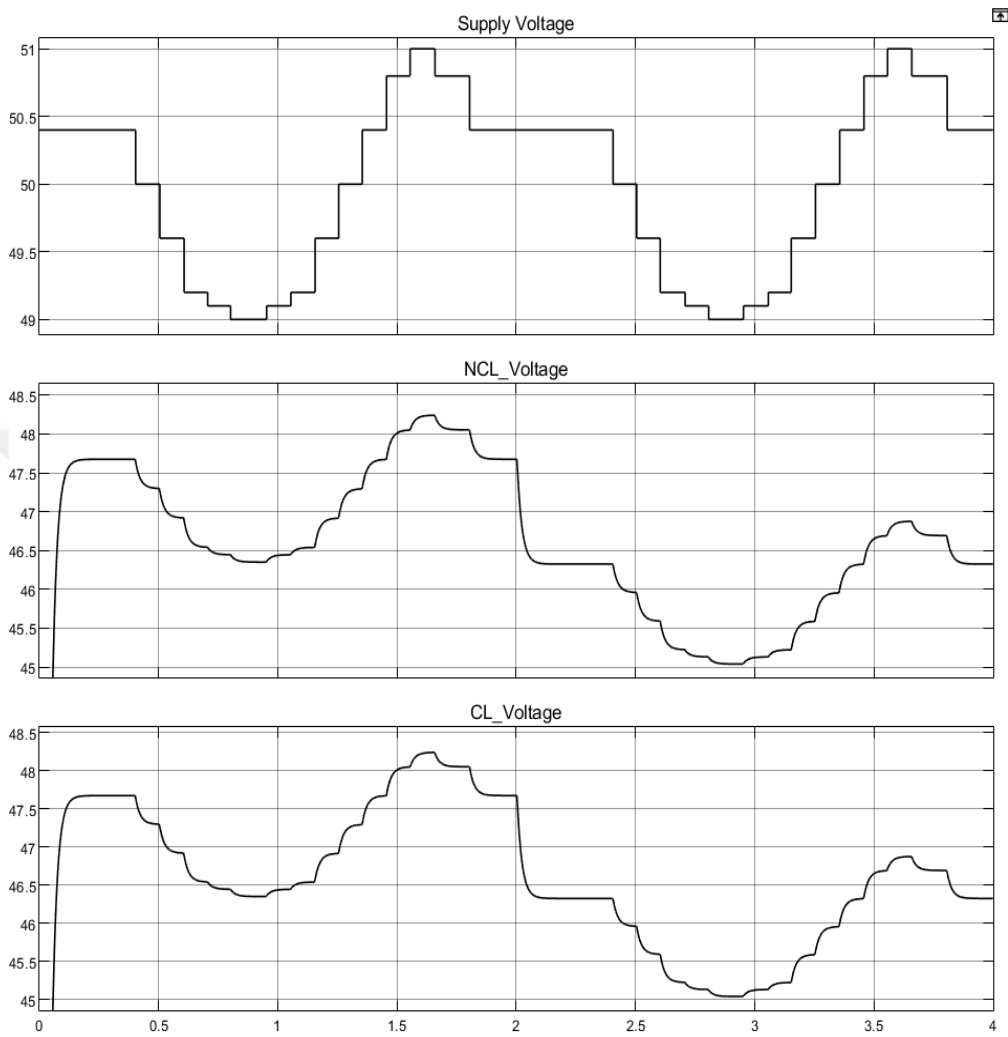


Figure 5.8. Voltage Levels of Loads without DCES by Changing Load

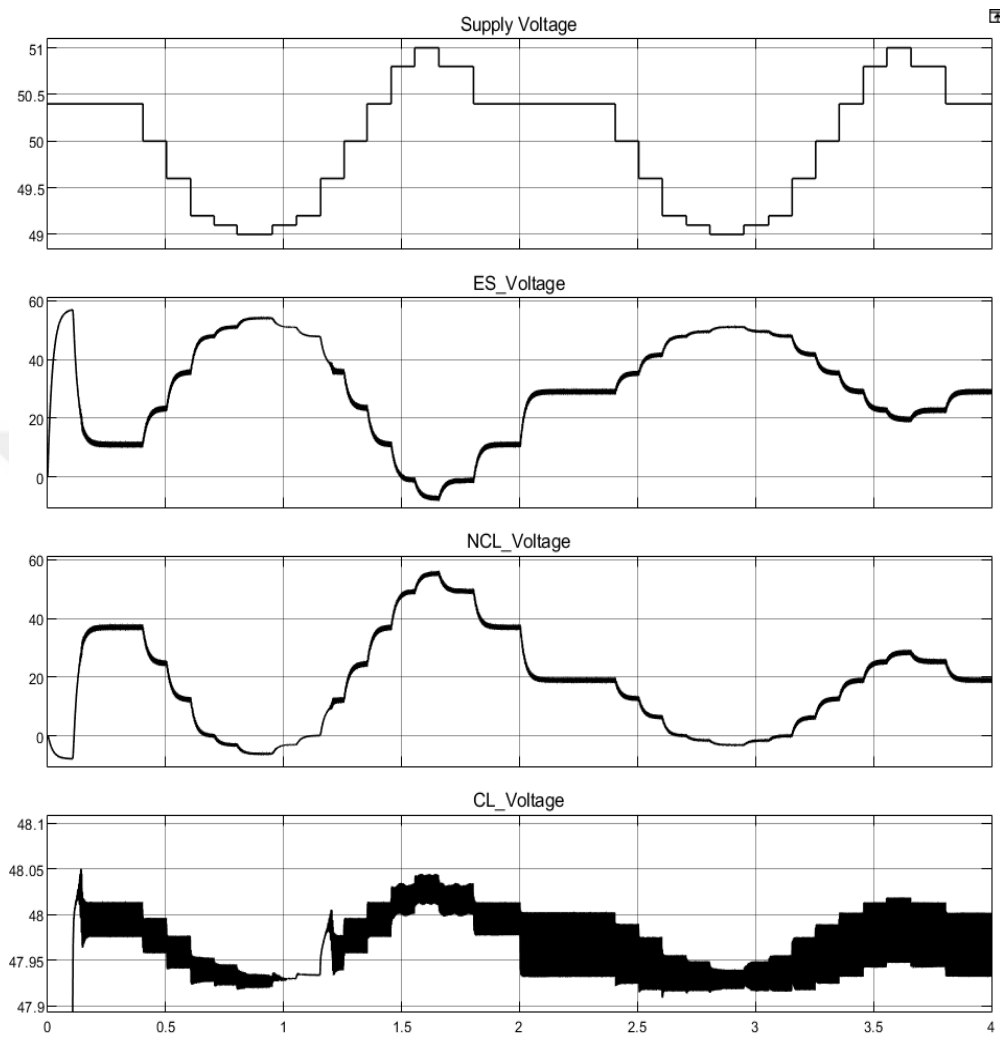


Figure 5.9. Voltage Levels of Proposed Topology by Changing Load

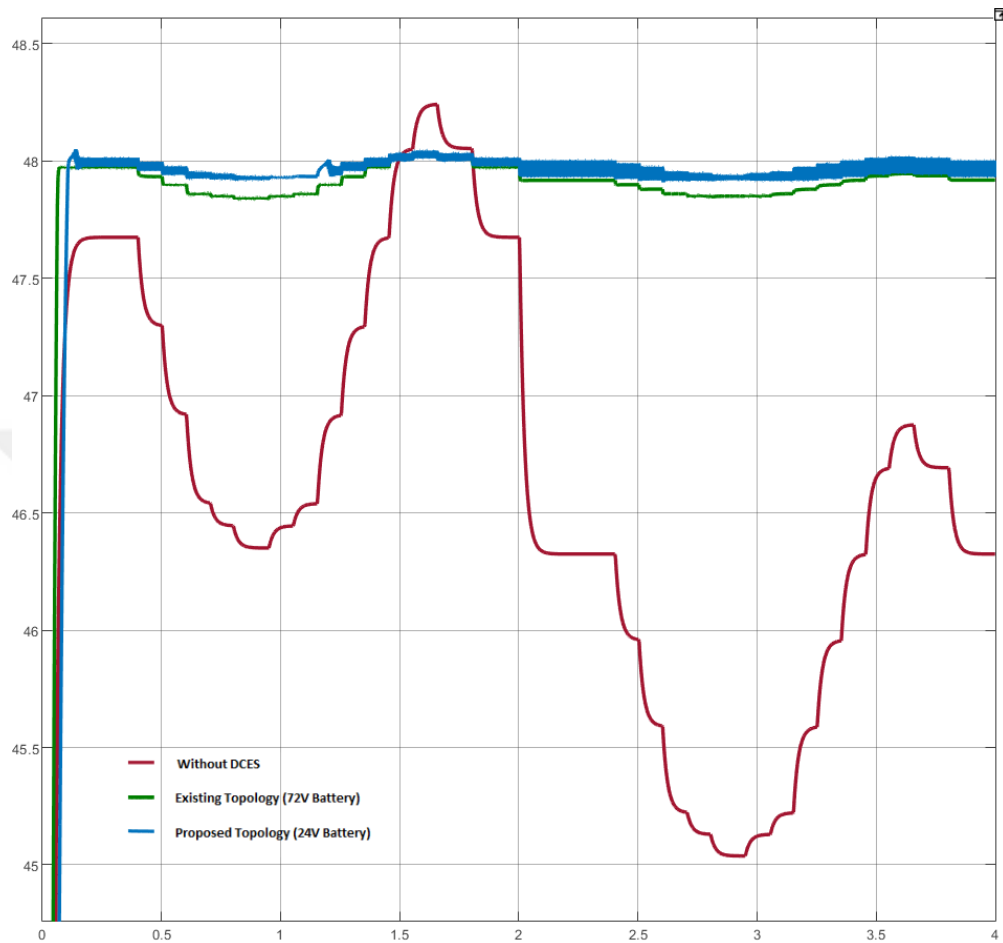


Figure 5.10. Comparison of Voltage Levels of Topologies by Changing Load

6. CONCLUSION

In this thesis, a DC Electric Spring (DCES) consisted of Half-Bridge DC-DC Converter integrated with Z-Source DC-DC Converter is modeled and simulated by using MATLAB/Simulink. The proposed DCES is applied into a DC Microgrid comprising a DC voltage source, Critical Load (CL) and Non-Critical Load (NCL). In this study DCES is connected series with NCL as a smart load form.

DC Microgrid supplied from Renewable Energy Sources (RES) cannot maintain the stable voltage because of intermittent nature of RESs. DCES is aimed to remove voltage fluctuations from Point of Common Coupling (PCC) and improves the voltage quality on CL.

Three different DC Microgrid is modeled and compared in two different cases. The first microgrid which is proposed by (Mok et al., 2016) is shown in Figure 5.2. In second microgrid, DCES is not used, CL and NCL are connected to PCC directly. And the proposed circuit is shown in Figure 5.1.

In the first case, intermittent nature of RES is simulated and 49-51V changing voltage is applied for three circuits simultaneously. Results show that, DCES has ability to maintain stable voltage on CL. With the advantages of proposed circuit topology, this can be done by reduced battery voltage.

Second case shows that, when any load change occurs in NCL, DCES can compensate the power change on PCC and keeps the voltage level stable for CL. The proposed circuit still maintains the voltage level between tolerances and uses less battery.

As a result, integration of Z-Source DC-DC Converter into Half-Bridge DC-DC Converter not only advantageous of reduced inrush current, ease of control and bipolar output voltage, but also enhances the voltage gain well and reduces the cost of battery bank. These advantages make the proposed topology attractive and cost effective according to existing topology.



REFERENCES

- Anderson J, Peng FZ. 2008. Four quasi-Z-source inverters. 2008 IEEE Power Electronics Specialists Conference. IEEE. p. 2743-2749.
- Cao D, Peng FZ. 2009. A family of Z-source and quasi-Z-source DC-DC converters. 2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition. IEEE. p. 1097-1101.
- Chen X, Shi M, Sun H, Li Y, He HJIToIE. 2017. Distributed cooperative control and stability analysis of multiple DC electric springs in a DC microgrid. 65: 5611-5622.
- Chen Z, Zhou J, Ren C, Wang Y. 2020. Distributed Cooperative Control of Multiple DC Electric Springs for Voltage Regulation in DC Microgrid. 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE). IEEE. p. 538-542.
- Fang X. 2008. A novel Z-source dc-dc converter. 2008 IEEE International Conference on Industrial Technology. IEEE. p. 1-4.
- Fang X, Ji X. 2008. Bidirectional power flow Z-source dc-dc converter. 2008 IEEE Vehicle Power and Propulsion Conference. IEEE. p. 1-5.
- Gawande S, Nagpure AR, Dhawad K, Chaturvedi P. 2020. Characteristics Behavior of Shunt DC Electric Spring for Mitigating DC Microgrid Issues. 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC). IEEE. p. 1-6.
- Gordo E, Khalaf N, Strangeowl T, Dolino R, Bennett NJSC, Miyamura High School. 2015. Factors affecting solar power production efficiency.
- Hashem RA, Soliman Y, Al-Sharm S, Massoud A. 2018. Design of an electric spring for power quality improvement in PV-based DC grid. 2018 IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE). IEEE. p. 156-161.

- Hui SY, Lee CK, Wu FFJIToSG. 2012. Electric springs—A new smart grid technology. 3: 1552-1561.
- Jeung Y-C, Le DD, Lee D-CJIA. 2019. Analysis and Design of DC-Bus Voltage Controller of Energy Storage Systems in DC Microgrids. 7: 126696-126708.
- Karami M, Cuzner RM. 2016. A distributed controller for DC microgrids stability enhancement. 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA). IEEE. p. 556-561.
- Lee C, Tan S, Wu F, Hui S, Chaudhuri B. 2013a. Use of Hooke's law for stabilizing future smart grid—The electric spring concept. 2013 IEEE Energy Conversion Congress and Exposition. IEEE. p. 5253-5257.
- Lee CK, Cheng KL, Ng WM. 2013b. Load characterisation of electric spring. 2013 IEEE energy conversion congress and exposition. IEEE. p. 4665-4670.
- Li X, Guo L, Wang C, Zhang S, Rong Y, Feng Y, Li Y. 2016. Robust and autonomous dc bus voltage control and stability analysis for a dc microgrid. 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia). IEEE. p. 3708-3714.
- Loh PC, Blaabjerg F, Wong CP. 2006. Comparative evaluation of pulse-width modulation strategies for Z-source neutral-point-clamped inverter. 2006 37th IEEE Power Electronics Specialists Conference. IEEE. p. 1-7.
- Loh PC, Gao F, Blaabjerg F, Feng SYC, Soon KNJJIToIA. 2007. Pulsewidth-modulated Z -source neutral-point-clamped inverter. 43: 1295-1308.
- Mok K-T, Wang M-H, Tan S-C, Hui S-Y. 2015. DC electric springs-An emerging technology for DC grids. 2015 IEEE applied power electronics conference and exposition (APEC). IEEE. p. 684-690.
- Mok K-T, Wang M-H, Tan S-C, Hui SRJIToPE. 2016. DC electric springs—A technology for stabilizing dc power distribution systems. 32: 1088-1105.
- Rashid MH. 2017. Power electronics handbook. Butterworth-Heinemann

- Shen H, Zhang B, Qiu DJIToIE. 2016. Hybrid Z-source boost DC–DC converters. 64: 310-319.
- Wang M-H, Mok K-T, Tan S-C, Hui S-YR. 2015. Series and shunt DC electric springs. 2015 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE. p. 6683-6690.
- Wang M-H, Mok K-T, Tan S-C, Hui SJIToSG. 2016a. Multifunctional DC electric springs for improving voltage quality of DC grids. 9: 2248-2258.
- Wang M-H, Yan S, Tan S-C, Hui SYRJIToPE. 2017. Hybrid-DC electric springs for DC voltage regulation and harmonic cancellation in DC microgrids. 33: 1167-1177.
- Wang M-H, Yan S, Tan S-C, Xu Z, Hui SYJIToPE. 2019a. Decentralized control of DC electric springs for storage reduction in DC microgrids. 35: 4634-4646.
- Wang M, He Y, Xu X, Dong Z, Lei YJIA. 2021. A Review of AC and DC Electric Springs. 9: 14398-14408.
- Wang Q, Cheng M, Jiang Y, Chen Z, Deng F, Wang Z. 2016b. DC electric springs with DC/DC converters. 2016 IEEE 8th international power electronics and motion control conference (IPEMC-ECCE Asia). IEEE. p. 3268-3273.
- Wang Q, Zha D, Deng F, Cheng M, Buja GJIPE. 2019b. A topology of DC electric springs for DC household applications. 12: 1241-1248.
- Xu C, Cheng K. 2011. A survey of distributed power system—AC versus DC distributed power system. 2011 4th International Conference on Power Electronics Systems and Applications. IEEE. p. 1-12.
- Yang Y, Tan S-C, Hui SYRJIToSG. 2017. Mitigating distribution power loss of DC microgrids with DC electric springs. 9: 5897-5906.

Zha D, Wang Q, Cheng M, Deng F, Buja G. 2019. Distributed Cooperative Control for Multiple DC Electric Springs with Novel Topologies Applied in DC Microgrid. 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG). IEEE. p. 648-652.

Zhang G, Zhang B, Li Z. 2018. Designing impedance networks converters. Springer

Zhao X, Yu Y, Cheng X, Wei Z, Ma M. 2017. A novel control strategy in low-voltage DC microgrid. 2017 Chinese Automation Congress (CAC). IEEE. p. 6055-6059.

BIOGRAPHY

He received his Bachelor of Science (B.S) degree in Electrical-Electronics Engineering Department from Çukurova University in 2016. He started Master of Science (MSc) education in Electrical-Electronics Engineering Department of Çukurova University. He has been working as an Electrical and Automation Engineer in Tosyali Toyo Çelik A.Ş. since 2016.

