

OPTIMUM PLACEMENT OF HIGH ENERGY INDUCTORS FOR CAPACITIVE
PULSE POWER SUPPLIES

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ABSTRACT

OPTIMUM PLACEMENT OF HIGH ENERGY INDUCTORS FOR CAPACITIVE PULSE POWER SUPPLIES

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Electromagnetic launcher (EML) systems convert electrical energy into mechanical energy. A large amount of energy must be supplied in a short time period to provide the necessary acceleration for the projectile. This type of energy is generally provided by capacitive pulsed power supplies (PPS). Many PPS units are connected in parallel to increase the total energy. Each module of a capacitive PPS includes high energy capacitor, shaping inductor, and semiconductors. The shaping inductors are air-core type inductors that are used to limit maximum current of the module. Since the shaping inductors of different modules are placed close by to achieve a compact design, their magnetic fields affect each other. If this magnetic coupling leads to a high enough negative induced voltage in non-conducting modules, the freewheeling diode may fail if the particular module is fired as the diode is open. Thus, protection systems that avoid the activation of a modules while their diodes are in conduction are used in EML systems. The protection system avoids the fault but decreases the energy of the supply. This study proposes a design methodology that determines the positions and orientations of shaping inductors as well as the switching sequence to

avoid semiconductor fault with a compact power supply. The design starts by determination of the physical dimensions of possible inductors with the desired inductance value and also capable of withstanding lateral electromagnetic forces by using 2D finite element analysis (FEA) simulations. The distances between the inductors are determined by an iterative approach by considering the different pre-defined placements. In this method, 3D FEA models are used to calculate the inductance matrix, which are used to estimate the induced voltages in other inductors and also in the system level simulation models. Finally, an optimum switching algorithm is presented that selects the most appropriate module firing sequence for a switching sequence.

Keywords: Pulse power supply modelling, shaping inductor, air-core inductor, inductor placement, pulse power supply switching

ÖZ

KAPASİTİF DARBE GÜÇ KAYNAKLARINDA KULLANILAN YÜKSEK GÜÇ BOBİNLERİNİN OPTİMUM YERLEŞİMİ

GÜNGEN, İBRAHİM

Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü

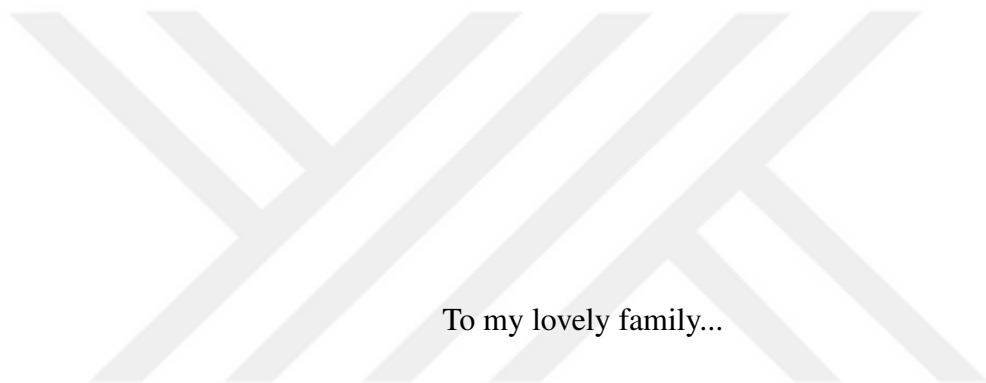
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Elektromanyetik fırlatıcı (EMF) sistemleri, elektrik enerjisini mekanik enerjiye dönüştürür. Mermi için gerekli ivmeyi sağlamak için kısa sürede büyük miktarda enerji sağlanmalıdır. Bu enerji türü genellikle kapasitif darbe güç kaynakları (DGK) ile sağlanır. EMF sistemlerinin toplam enerjisini artırmak için birçok darbe güç kaynağı ünitesi paralel olarak bağlanır. Kapasitif DGK'nın her bir modülü, yüksek enerjili kondansatör, şekillendirme bobini ve yarı iletkenler içerir. Şekillendirme bobinleri, modülün maksimum akımını sınırlamak için kullanılan hava çekirdekli bobinlerdir. Kompakt bir tasarım elde etmek için farklı modüllerin bobinleri yakın yerleştirildiğinden, manyetik alanları birbirini etkiler. Bu manyetik etki, ateşlenmeyen modüllerde yeterince yüksek bir negatif indüklenmiş voltaja yol açarsa, diyotlar ilettime geçer ve iletimdeyken bu modül ateşlenirse diyot bozulabilir. EMF sistemlerinde diyotların bu şekilde ilettime geçmesi durumunda ilgili modülün aktivasyonunu önleyen koruma sistemleri kullanılmaktadır. Koruma sistemleri arızayı önler fakat sistemin toplam enerjisini azaltır. Bu çalışma, kompakt bir güç kaynağı ile yarı iletken arızasını önlemek için bobinlerin konumlarını ve yönelimlerini, bunların yanında anahtar-

lama sırasını belirleyen bir tasarım metodolojisi önermektedir. Tasarım, istenen endüktans değerine sahip ve belirlenen yanal kuvvet sınırının altındaki olası indüktörlerin fiziksel boyutlarının belirlenmesiyle başlar ve 2 boyutlu sonlu eleman analiziyle simülasyonları yapılır. İndüktörler arasındaki mesafeler, önceden tanımlanmış farklı yerleşimler dikkate alınarak bir döngü içerisinde belirlenir. Bu yöntemde, diğer indüktörlerde ve sistem düzeyinde indüklenen gerilimleri tahmin etmek için kullanılan endüktans matrisini hesaplamak için 3 boyutlu sonlu eleman analizi modelleri kullanılır. Son olarak, her bir ateşleme dizisi adımı için en uygun modülleri seçmek adına optimum anahtarlama algoritması tasarlanmıştır.

Anahtar Kelimeler: Darbe güç kaynağı modellenmesi, şekillendirme bobini, hava çekirdekli bobin, bobin yerleşimi, darbe güç kaynağı anahtarlama



To my lovely family...

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LIST OF ABBREVIATIONS

EML	Electromagnetic Launcher
PPS	Pulse Power Supply
CPPS	Capacitive Pulse Power Supply
FEM	Finite Element Method
L	Inductance
C	Capacitance
AC	Alternating Current
DC	Direct Current
1D	1 Dimensional
2D	2 Dimensional
3D	3 Dimensional
D_{horz}	Horizontal Distances between Inductors
D_{vert}	Horizontal Distances between Inductors
h_{ind}	Height of the Inductor
r_{in}	Inner radius of the Inductor
N_{turn}	Number of turns of the Inductor
L_{scr}	Inductance of the Thyristors
L_d	Inductance of the Diodes
L_c	Inductance of the Capacitors
RI_{HF}	High Frequency Resistance of the Inductor
RI_{LF}	Low Frequency Resistance of the Inductor
L_{cable}	Inductance of the Cables
L_{cable}	Resistance of the Cables
V_d	Diode Voltage



CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

Capacitive pulse power supplies (CPPSs) enable us to use a high amount of electrical energy in very short time intervals. Because of that, these could be used in very different applications. Electromagnetic launcher (EML), also called Railgun, systems are one of them. To reach a higher armature speed, the energy of the power supply should be increased. The energy of the capacitor; current, and voltage capabilities of semiconductors are limited so that a high amount of energy could be obtained by connecting many PPS modules that has smaller energy capacity in parallel. Pulse power modules have 3 main parts; capacitor blocks, semiconductor blocks also called pulser, and shaping inductors. When any module is fired, a high amount of current passes in a short time interval. The high amount of current leads to high amount of electromagnetic field, which can link the other shaping inductors. Thus, induced voltages are seen on these shaping inductors. These induced voltage values could cause freewheeling diodes to conduct. If the module is fired when the freewheeling diode is conducting, diodes brake and the module becomes unusable as illustrated in Figure 1.1.

Moreover, the design of the shaping inductor is complicated, since the a high amount of electromagnetic flux leads to a high amount of force on the turns of the inductor. Lateral pressure values could defect insulation between copper layers and cause an inductor fault. Moreover, calculation of the inductance value is not straight forward because of the air core structure. Thus, it is hard to estimate the effective length of

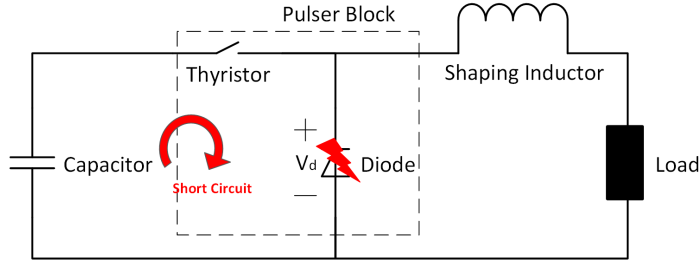


Figure 1.1: PPS module failure mechanism

the energy-storing volume inside the coil.

These 2 main problems show us the requirement for a new shaping inductor placement method to prevent unwanted faults.

1.2 Proposed Methods and Models

To prevent unwanted results, shaping inductors should be designed carefully, placement of these should be appropriate, and switching sequences of modules should be chosen carefully. This study proposes a generic methodology that is developed to design an air-cored inductor, decide the minimum distances between modules and orientation of each inductor and finally proposes switching sequences for a safe operation. The methodology includes 2D finite element analysis(FEA) to design inductors by calculating inductance, resistance, and lateral pressure; 3D finite element analysis to arrange inductor orientation and the spacing between inductors; Simulink analysis for overall system simulation and optimum switching algorithm. The proposed method gives optimum inductor design, placement for the inductors, and then optimum switching for optimum placement configurations by using COMSOL and Simulink softwares controlled by a Matlab code.

1.3 Contributions and Novelties

The contributions of this study to the literature can be summarized as follows:

- Optimum inductor design is carried out according to the pressure, inductance, and resistance by using 2D FEA.
- Overall placement and orientation analysis is made for each inductor to find optimum orientation.
- Optimum spacing are detected for an orientation and inductor type.
- Modules of the each switching sequence step are arranged to make the system safer.

In the literature, researchers are focused on topics as triggering strategies, fault protection systems etc, to the best of my knowledge, such a work does not exist in the literature, it will be a critical study to achieve compact and safe system.

1.4 The Outline of the Thesis

In Chapter 2, general information and literature review on the EML system and its sub-components is given. Among the sub-components, the PPS system is detailed, and the general structures and designs of the circuit elements used in PPS modules are examined.

In Chapter 3, the mechanism of the failure of the designed high-energy pulse power supply coils is explained. The minimum coil inductance value is calculated according to the voltage and energy level specified in the system requirements, and the maximum current value is determined based on the semiconductor limits. Then, the coils were designed within the constraints determined by considering the lateral pressure, which is the cause of the failure, and the most suitable inductor designs are selected. Coil selection is made according to resistance, pressure and inductance value. Minimum lateral pressure and resistance are aimed for the determined inductance value.

Chapter 4 includes the method developed to find the optimum placement of any air-core cylindrical inductors. Firstly, the interactions between the coils of the modules in the container are examined. It is stated and illustrated that the interaction between the coils causes errors that are difficult to correct. Orientation and placement analyzes for the coil designs selected in Chapter 3 were performed with COMSOL. With these analyses, mutual inductance matrix was obtained for each coil and location. System simulations were made by taking the worst of the best switching scenarios and using the mutual inductance matrix. As a result of the analyzes and simulations, the optimum distance values between the coils for each placement combination were found.

Chapter 5 includes the method to find the optimum coils to be switched for each switching step in a determined switching sequence by examining the switching combinations and minimizing the danger. This method is called the Optimal Switching Algorithm.

Finally, Chapter 6 gives the conclusion and explains the outcome of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 General Information on Electromagnetic Launcher Systems

Electromagnetic launcher (EML) systems convert first electric energy to electromagnetic energy and then convert this to mechanical energy. EML's are developed for many applications. Some of these listed below [25]:

- Hypervelocity electromagnetic guns
- Electromagnetic launch of aircraft
- Acceleration of guided projectiles to hypervelocity
- Electromagnetic protection
- Other weapons systems that used electromagnetic energy

According to McNab's belief, the first electric gun that is called SIVA or The Destroyer appeared in an advertisement in the US in 1884 as shown Figure 2.1 [1]. The first studies on electromagnetic launchers started in the 19th century, but the great advances and developments in this technology took place in the 20th century. Some developments were made and efforts are given by Norwegians in 1901, by Frenches in World War I, by Germans and Japan during World War II [1].

Electromagnetic launcher technology has been advancing for almost a century and a half starting from those years. Today, a lot of countries are working on their EML systems in parallel. These countries are USA (Navy Force, General Atomics etc.) [26], France and Germany (ISL) [27], Chine [28], Russia [29], England [30] and Turkey

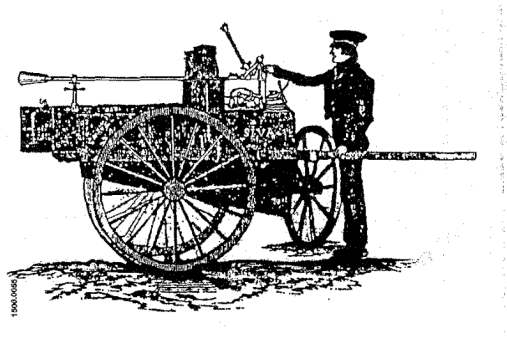


Figure 2.1: Benningfield's electric gun, SIVA, as shown in an 1844 advertisement [1]

[31]. Figure 2.2 shows EML systems and also Figure 2.3 shows rail of the EML system. This system can be placed on warships and military bases. The system is really heavy because of a heavy pulse power unit and barrels this situation is decreasing mobility. And also, it needs an electric supply to charge the system. EML systems include four main blocks. These are rails of the electromagnetic launcher, power supply unit that produces pulse power, high voltage capacitor charger, and control unit of the system. Pulse power capacitors are charged by a high voltage charger and then, switching times of modules and desired voltage levels are entered into the control unit. Finally, the fire button enables to pass the pulsated current through to rails and armature. Length of rails and energy of the pulse power supply unit should be compatible. Because, if they are not, when armature exits rail, discharged energy causes arc on the rail. Figure 2.4 shows an example EML system schematic. Also, Figure 2.5 shows mechanism of the rail and armature work.



Figure 2.2: Example of the EML system [2]



Figure 2.3: Example of the electromagnetic launcher [2]

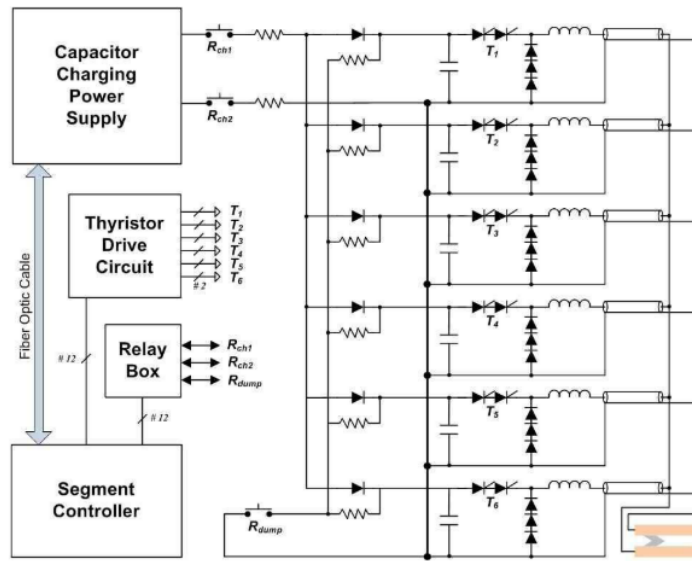


Figure 2.4: Schematic diagram of the 600-kJ segment [3]

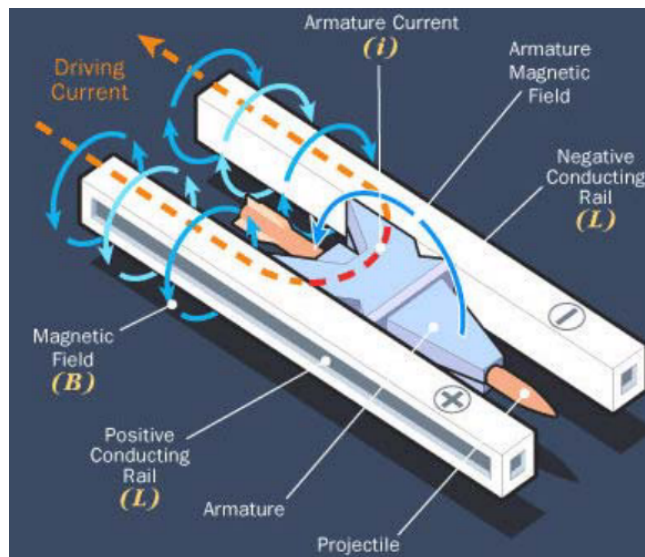


Figure 2.5: Illustration of the rail and armature [4]

2.1.1 Barrel and Armature of Electromagnetic Launcher

The barrel is one of the main subsystems of EML systems. Cross-section of a non-laminated barrel can be seen in Figure 2.6. The design of it is a very complicated and multidisciplinary. The caliber and length of the rail of the barrel are specified depending on the required energy level. On the barrel, there occurs a lot of electromagnetic and mechanical phenomenons like skin effect, velocity skin effect, proximity effect, lateral pressure, pressure based vibrations to be considered in the design.

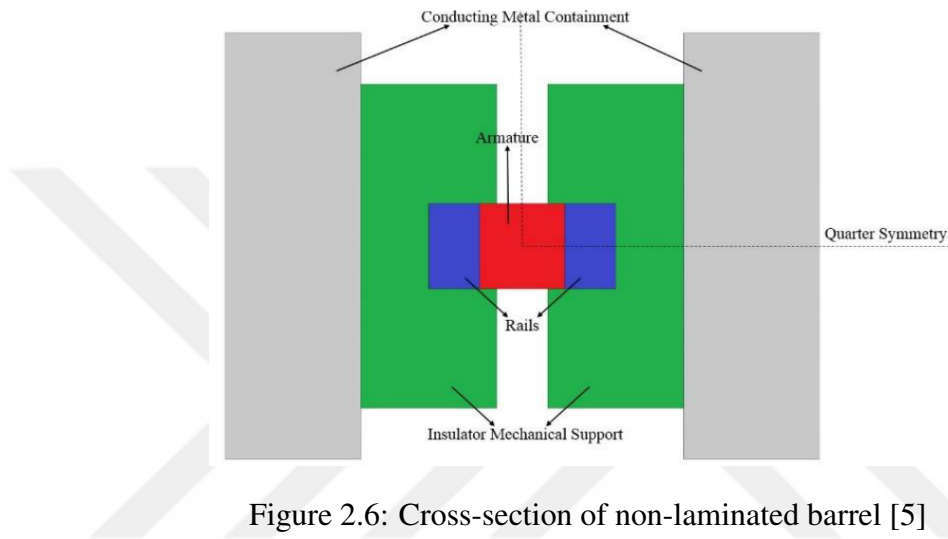


Figure 2.6: Cross-section of non-laminated barrel [5]

High conductive copper layers are placed into the metal containment with an insulation block to increase mechanical strength as can be seen Figure 2.6. The mechanical strength is important because of the lateral forces on the rail as Figure 2.7 shows. Rails are passing the currents in reverse directions thus the rails repel each other due to the Lorentz's forces in the outwards directions. Additionally, armature applies a pressure on the rail. In order to calculate deflection, different types of models and simulation setups are built like beam model [6], predicted displacement method [7], hybrid models [32] and so on. As shown in Figure 2.8, pressures on armature and rail do not distribute homogeneously. These methods gives us rough information on pressure and stress on rails and enables us to make an estimation about deflection location of rail.

Moreover, efficiency of the system is critical so that losses should be minimized. Pulse shaped current leads eddy losses on the metal blocks. Using a laminated metal

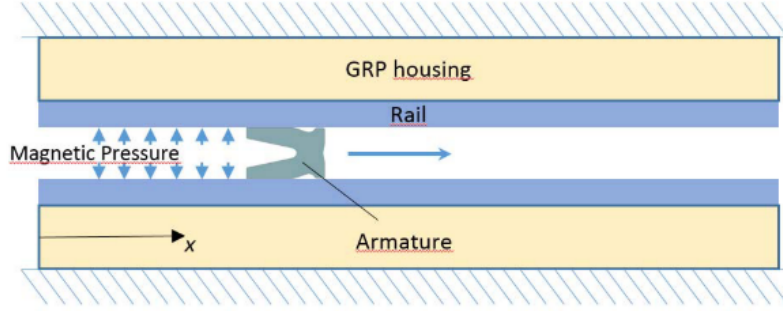


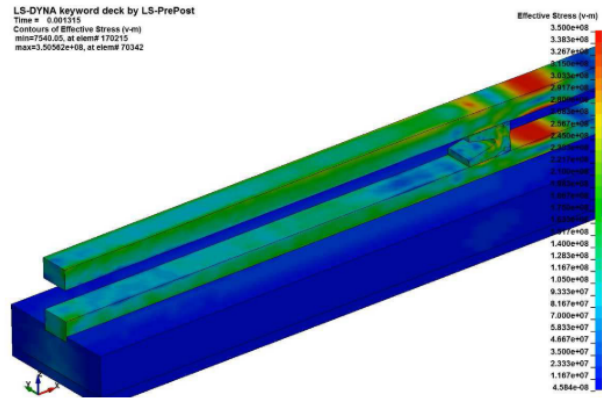
Figure 2.7: Magnetic force illustration [6]

containment can decrease eddy current losses on the core [5].

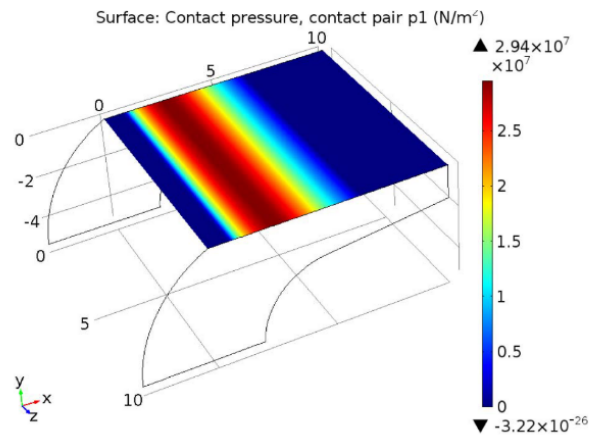
$$\mathbf{F}_{Lorentz} = \frac{1}{2} \frac{dL}{dx} \mathbf{I}^2 \quad (21)$$

Acceleration force of the armature is directly depend on L' (inductance per meter, $\frac{dL}{dx}$) and rail current as in (21). L' value depends on geometry of the rail. Asghar Keshtkar made simulations to show effects of dimensions on the L' value. As depicted in Figure 2.9, when width and height of the rail decrease, separation increases, hence L' increases [8]. Also, if separation 's' increase L' increases but efficiency may decrease because of parasitic mass [33]. As shown in Figure 2.10, launch package of the railgun includes projectile, armature and sabot pieces. If separation is high, armature and sabot should be bigger and heavier. Parasitic mass includes all launcher mass except projectile.

Distribution of the current on the rail and armature is another important phenomenon. Performance of the railgun systems directly depend on the current distribution. If it does not flow homogeneously, translations, deformations, overheating and faults could be seen on the rail. Moreover, efficiency decreases when current density is not homogeneous at the contact surface. To keep current density homogeneous and increase L' , different rail geometries are studied. Rectangular, convex and concave rail geometries are investigated and compared in [10] [33] [34]. Difference between maximum and minimum current densities at the contact surface is minimized with a better rail design. As Figure 2.11 shows with convex rail, current distributes more homogeneously than other types. Therefore, new studies are focusing on convex type



(a)



(b)

Figure 2.8: (a) Von Mises Stress of the rail [6], (b) Pressure distribution of armature contact surface [7]

rails. Also mechanical performances of the concave and convex type of rails are better than rectangular flat rail [10].

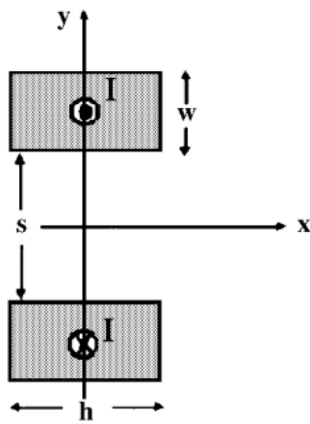


Figure 2.9: Cross-section of railgun [8]

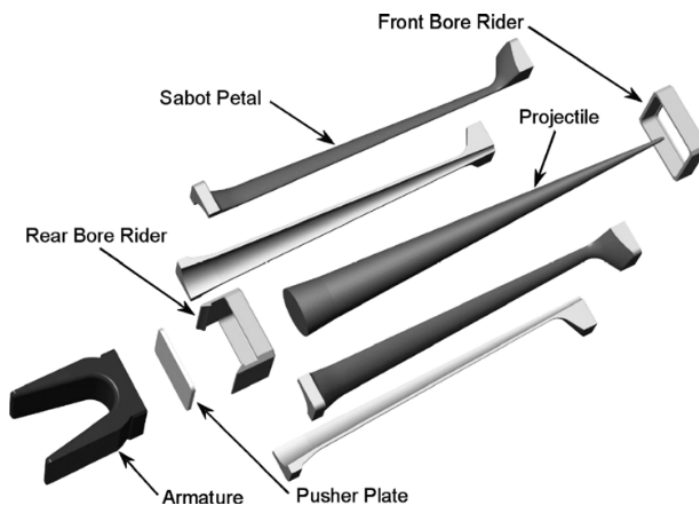
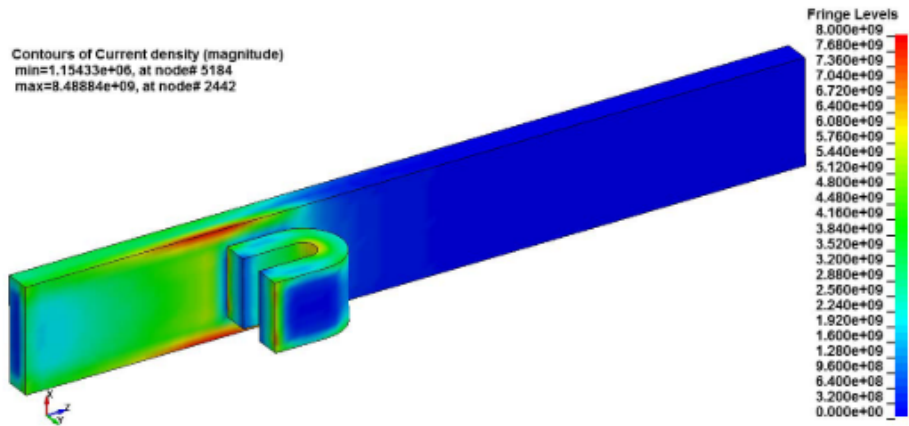
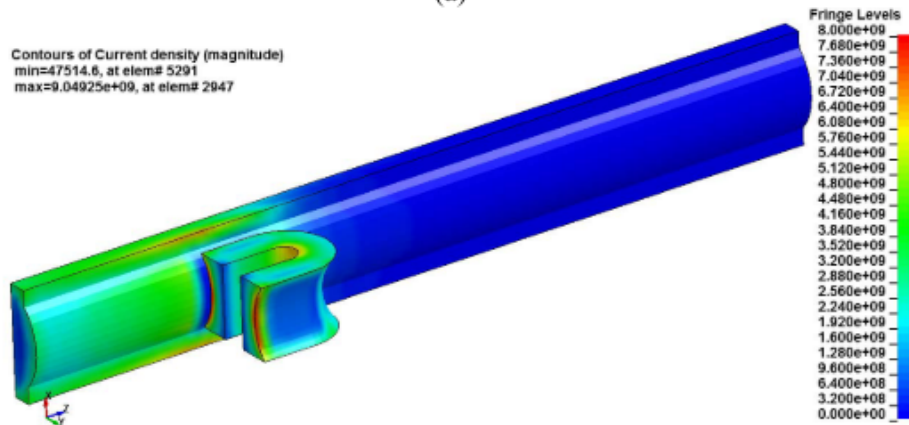


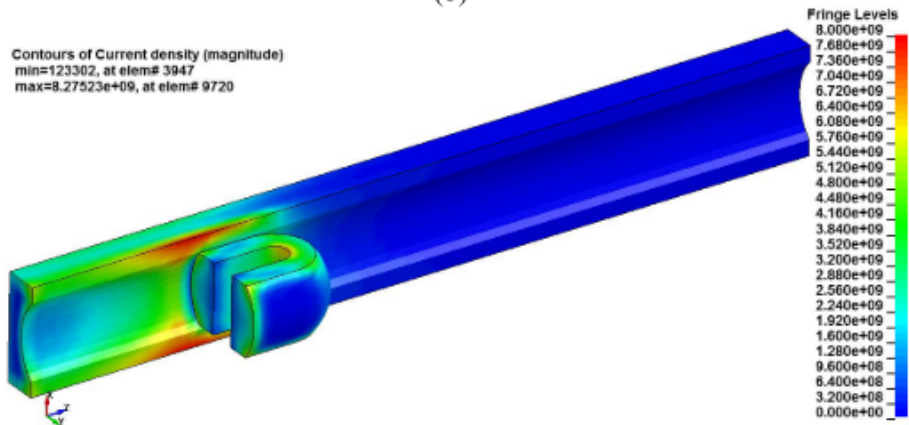
Figure 2.10: Launch package of the Railgun [9]



(a)



(b)



(c)

Figure 2.11: Current distribution of (a) Rectangular, (b) Convex and (c) Concave rail [10]

However, design of armature is another critical point. Parameters in Figure 2.12a should be optimized to make better design, prevent heating due to failure and make system more efficient. An example for an optimized armature and its current density distribution is shown in Figure 2.12b.

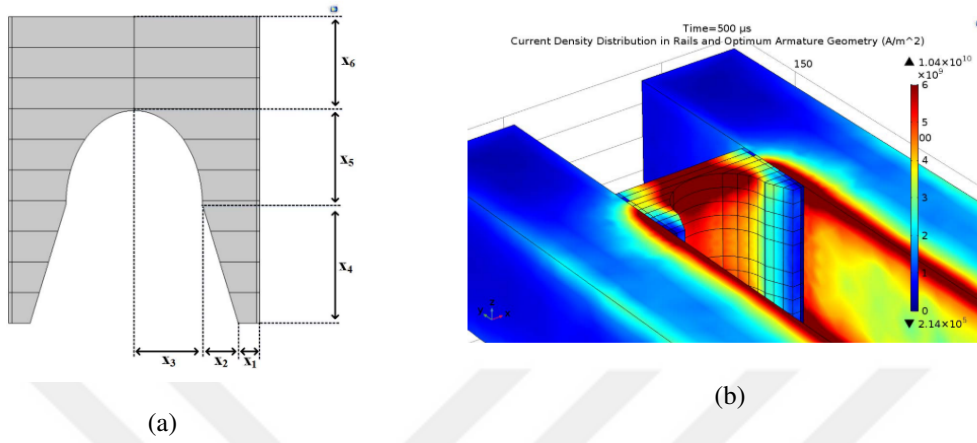


Figure 2.12: (a) Armature parameters for flat rail type, (b) Current distribution of the armature [11]

EML systems launch the armature and projectile at hyper-velocity (approximately over 2000 m/s). High velocity affects also the distribution of the current. This phenomenon is called velocity skin effect (VSE). To calculate and observe effects of VSE, transient magnetic simulations should be performed, armature position should change according to time and velocity [35]. In [12], 2D and 3D quasi-transient COMSOL models for VSE are compared. Figure 2.13 compares the current distribution with a stationary and a moving armature.

2.1.2 Pulse Power Supply

Due to unique characteristics of high power, pulse power technology is an important research area for both military and civil applications. Radiography, free electron laser, imploding liner, high power microwave, environment protection, medical treatment and electromagnetic launcher can be given as some application examples [36]. Capacitive pulse power supplies are used in electromagnetic launchers in general. Also, inductive pulse power supply (XRAM generator) concept is started to be used by

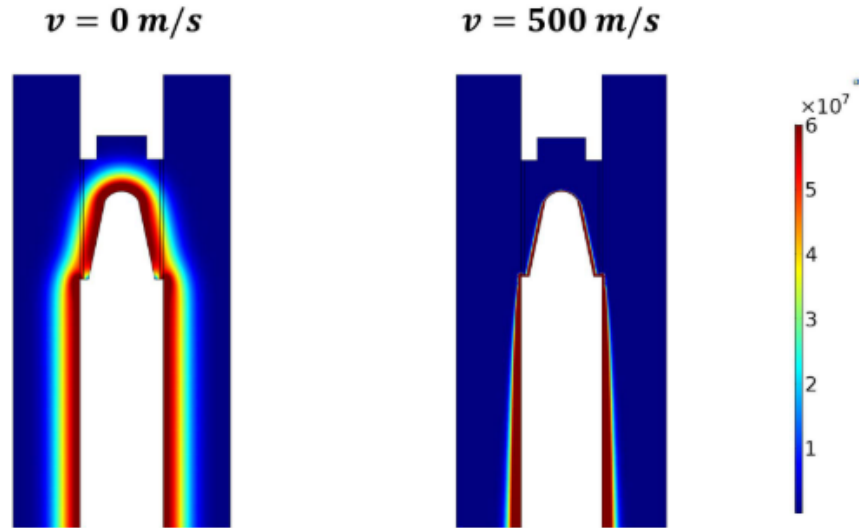


Figure 2.13: Effect of velocity on current distribution [12]

some researcher for EML systems.

2.1.2.1 Capacitive Pulse Power Supply

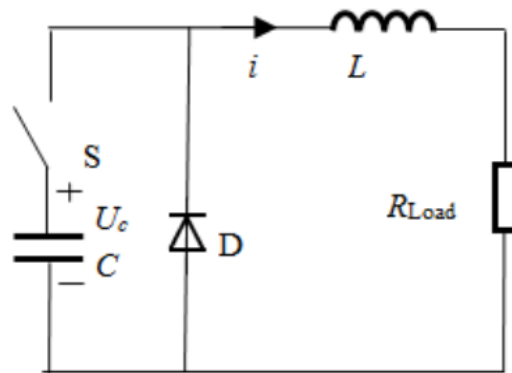


Figure 2.14: Capacitive pulse forming unit (pulse power supply) [13]

Electrical energy is stored in high voltage capacitor (C) at the capacitive pulse power supply. To prevent negative voltage on the capacitor, freewheeling diode is connected in parallel. To switch the capacitor, thyristors are used in general because they have low switching noise, good reliability and short time delay [37]. The current increases sharply, so that peak value of the current should be limited to shape the current. In

order to achieve this, shaping inductor (L) is used. Semiconductors, diodes and thyristors of PPS is packaged together and this system called as pulser. Figure 2.15 shows an example of the currents of the thyristor and diode and voltage of the capacitor of a PPS module. The maximum current of the pulse power supplies is limited by semiconductor features.

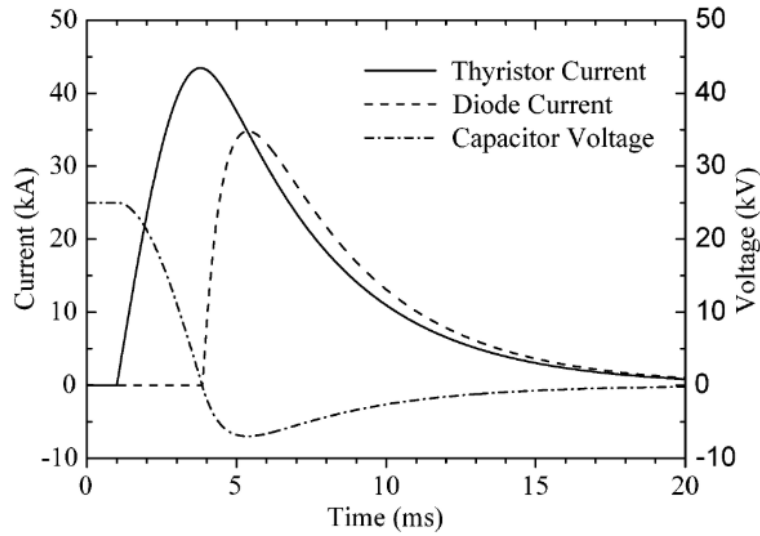


Figure 2.15: Example of the currents of PPS, diode and thyristor [14]

The energy density of PPS modules is very important. Because the railgun's energy source is the PPS modules, and wherever the railgun is taken, the modules must also be transported. Thus, researchers are working on increasing the energy density of the modules. Increasing energy density of the capacitors is very critical to achieve this goal [13]. Also, another design requirement is to reach high energy. Therefore, numerous PPS modules are connected in parallel to reach higher energy levels as discussed in [38], [39], [40], [14].

Components of the PPS are explained in the following text.

Capacitor

Capacitors are used in a lot of power electronics applications like storage of the energy, filtering the ripple voltage, DC voltage smoothing, and etc. In general, aluminum electrolytic capacitors and metallized film capacitors are used in the power electronics applications [41]. In pulse power supply of EMLs, metallized film capac-

itors are used. As shown in Figure 2.16, these type of capacitors consist of dielectric films with a metallic coating on the surface. The electrodes are made of very thin metal layers, which are usually made of aluminum or zinc, and evaporated onto the surface of the polymer film. Polypropylene (PP) or polyethylene terephthalate (PET) is mainly used as dielectric film [41]. These films can be specialized according to the application.

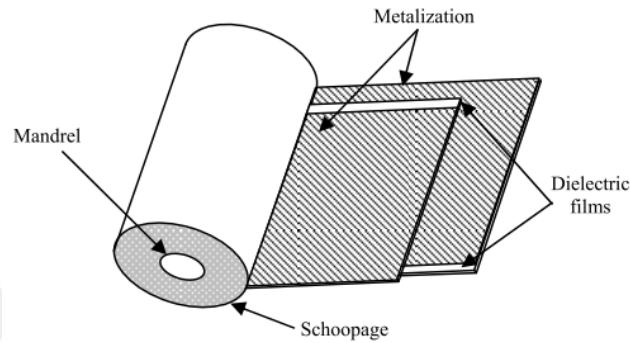


Figure 2.16: Structure of metalized film capacitors [15]

Shaping Inductor

High amount of current is supplied to the load in a short time interval. Therefore, high frequency and high energy air core inductors are used in pulse power applications. Design of the pulse shaping inductor is very critical, since electromagnetic lateral forces inside the inductor could lead to faults of the inductor [23]. Also, inductance value affects the peak current of the module. These values should be compatible. Moreover, a strong magnetic flux is produced by the inductor. Because of the strong magnetic flux, high eddy currents can be induced on the conductive structure around the inductor. If eddy current on the metal and inductor current interacts, high magnetic forces could be generated between the mechanical structure and the inductor [42]. Analyses should be made to prevent this unwanted dangerous forces.

Besides these, calculation of the inductance values of air-core inductors is not straight forward. Since, electromagnetic energy is stored inside the coil and in the air right next to it. Effective length of the coil changes according to the geometry. Equation 22, 23, 24 are derived in [43], [44, 45] and [46] to calculate air-core inductor's inductance

value, respectively. In these equations, N is number of turns μ_0 is permeability of free space and outer dimensions are given in Figure 2.17. These formulas are generated based on the Wheeler's formula in general [47], [48].

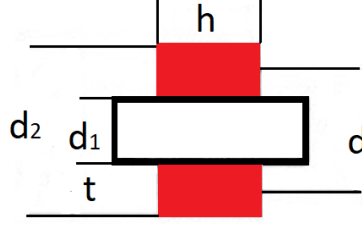


Figure 2.17: Air-core inductor parameters

$$L = \frac{0.008d^2N^2}{3d + 9h + 10t} \quad (\text{in mm}) \quad (22)$$

$$L = \frac{d^2N^2}{18d + 40h} \quad (\text{in inches}) \quad (23)$$

$$L = \mu_0 N \frac{d}{2} \left(\ln\left(\frac{8d}{d_{cable}}\right) - \frac{7}{4} \right) \quad (\text{in mm}) \quad (24)$$

(d_1 is the inner diameter, d_2 is the outer diameter, d is the mean diameter, d_{cable} is the diameter of the cable and h is the length of the coil and t is the thickness of the winding)

Pulser

Thyristors are used in PPS modules to switch the energy of the capacitors, and diodes are used to create freewheeling path. These semiconductors are clamped together and they are press-pack semiconductors [49]. Mechanical clamping of these semiconductors is very critical because if contact between components is not good, resistances increase and pulser blocks do not work at their full potential. The semiconductor block includes press-pack semiconductors that are thyristor (GTO) and diode, heat sinks, spacer and load spreaders as shown in Figures 2.18 and 2.19 [16].

In such a structure, contact pressure should be homogeneous to ensure a good contact. Clamping pressure and force values are specified in the datasheet of press-pack semi-

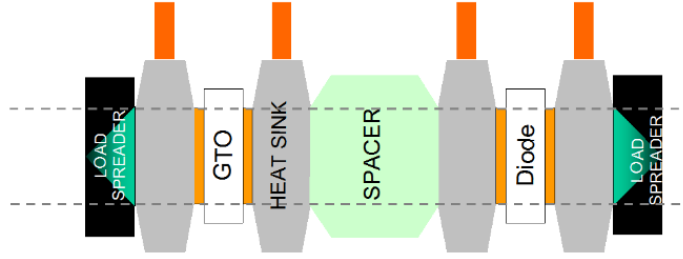


Figure 2.18: Illustration of a well designed stack [16]

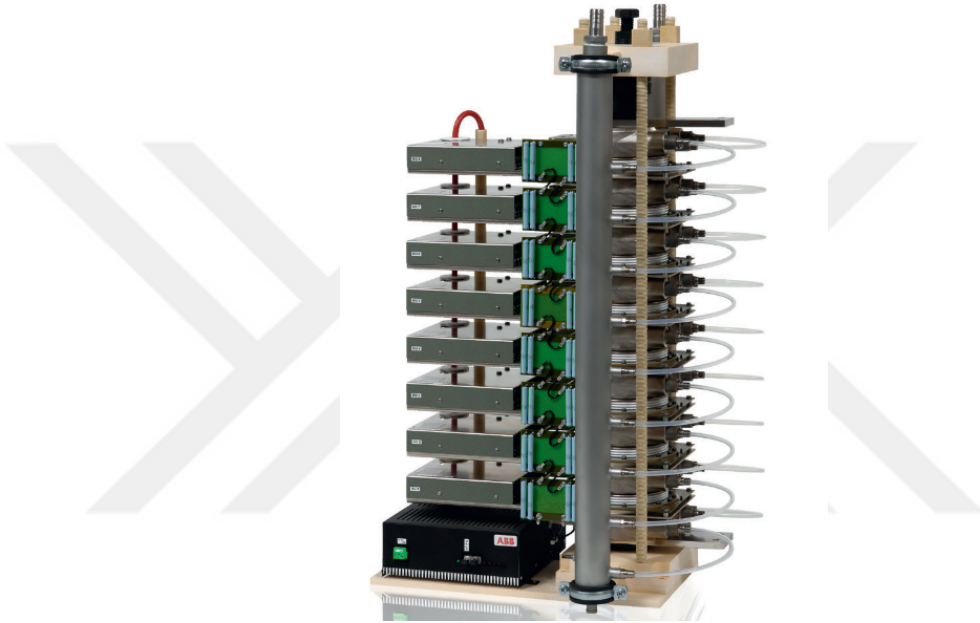


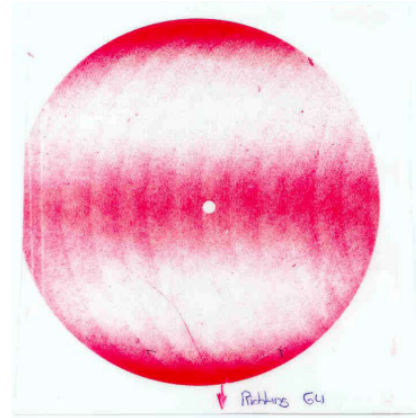
Figure 2.19: Example of a stack [16]

conductors. In order to measure contact pressure distribution, pressure sensitive films are used. Figure 2.21 shows an examples of the good and poor pressure distributions between two semiconductor surfaces.

Moreover, semiconductors used in pulser structures should have small conduct resistance to increase efficiency. So, components are chosen according to the semiconductor loss. Rectifier diodes are used as diodes of pulser and phase-controlled thyristors are used as thyristors of pulser. Semiconductors in [50] and [51] can be examples of the high voltage pulser components with high efficiency.



(a)



(b)

Figure 2.20: (a) Good contact pressure, (b) Poor contact pressure [16]



(a)



(b)

Figure 2.21: (a) High voltage rectifier diodes [17], (b) High voltage phase controller thyristors [18]

2.1.3 Control System of Electromagnetic Launcher

A PPS system includes many PPS modules. If all of the modules are discharged at the same time (at $t=0$), current on the rails and the armature reach one high peak point as shown with blue line in Figure 2.22, and a result of this high amount of lateral electromagnetic force occurs on the rails. This kind of current could lead to mechanical damage. And also waveform of the rail currents affects the efficiency of the system and velocity of the projectile. Moreover, specifying and setting of the muzzle velocity of the projectile is important for ballistic calculation of the ultrasonic projectile. Thus, current waveform should be optimized for efficiency, speed and mechanical safety [19]. So, the modules should be switched one by one to obtain required load current. Switching time sequences are one of the design aspects of the system, as the current on the rail directly depends on the these sequences. To adjust the current shape, modules are switched at different times with time delays in the range of microseconds. Shaped current waveform by delaying the discharging times of the modules (red line) are shown in Figure 2.22. To achieve this, high speed components like photoelectric devices, fiber-optic cables for transmission of the firing signals and DSP for processing the signals should be used [20]. Figure 2.23 shows an example control system of the EML systems.

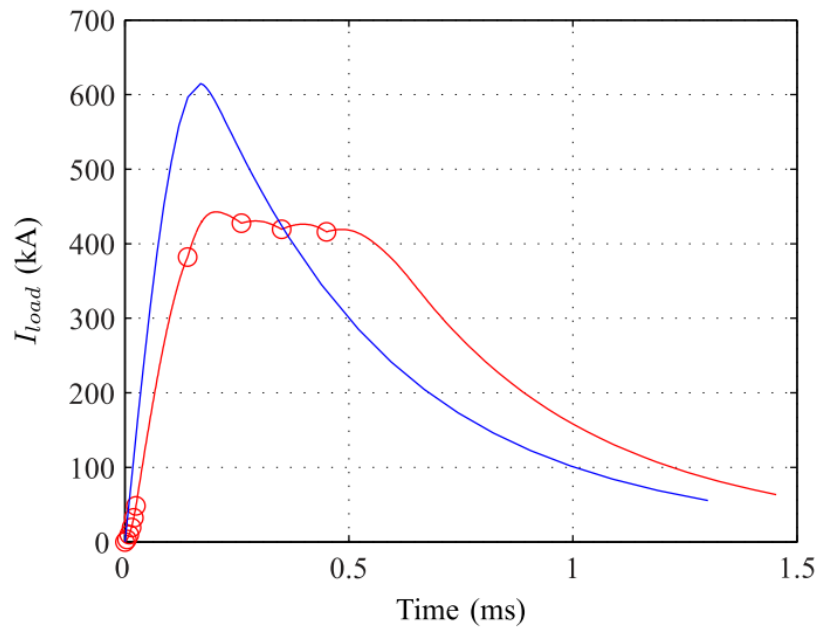


Figure 2.22: Current types of the rail [19]

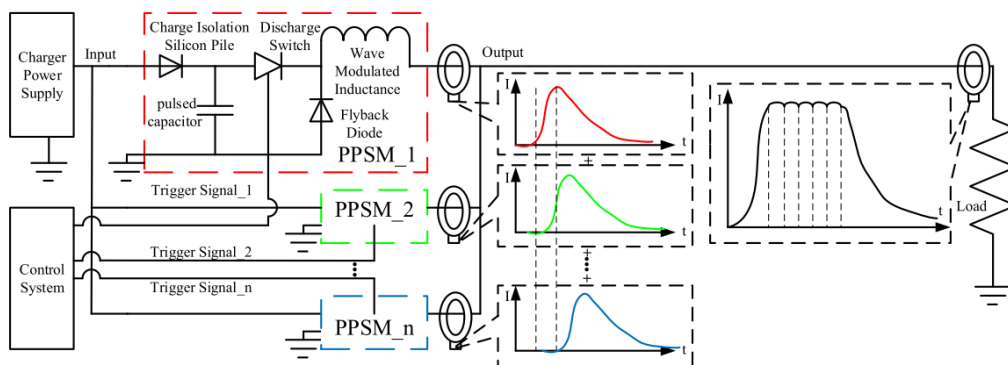


Figure 2.23: Control system of EML system [20]

CHAPTER 3

DESIGN OF AIR-CORE INDUCTOR

3.1 Overview of Design of Air-Core Inductors

Air core inductor of pulse power supplies, which can be called shaping inductor, is used to limit peak current when capacitor is discharged. Its value is important because the current peak should not exceed semiconductor limits. Pulse power supply module includes capacitors, inductor, and semiconductor blocks (Figure 3.1).

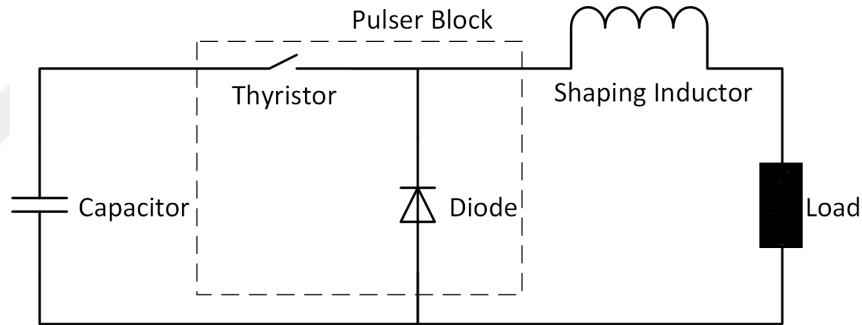


Figure 3.1: Basic circuit of capacitive PPS module

Block diagram of the algorithm used to design the shaping inductor is shown in Figure 3.2. At the beginning of the algorithm, the charging voltage, energy level, and semiconductor types of the PPS module are determined and then capacitance and inductance values are calculated based on these values. After that, the inductance value is verified by module simulation block by using Simulink software, and inductor dimensions are determined by considering the mechanical robustness of the inductor with the help of FEA.

Air-core cylindrical coils are generally used in capacitive PPS modules. This is be-

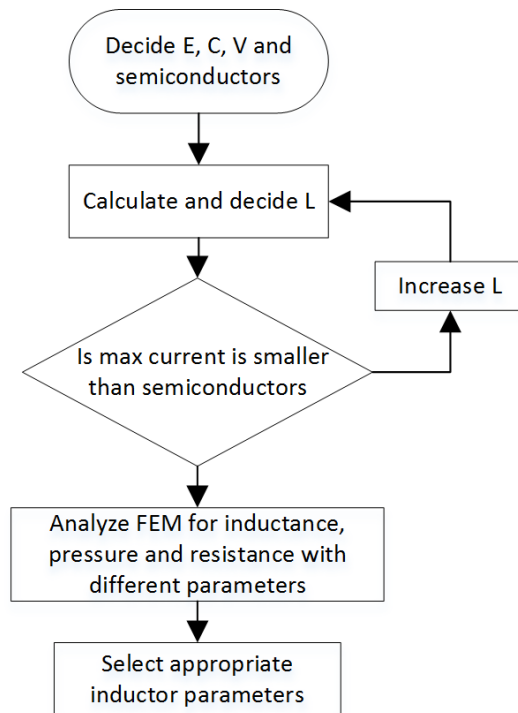
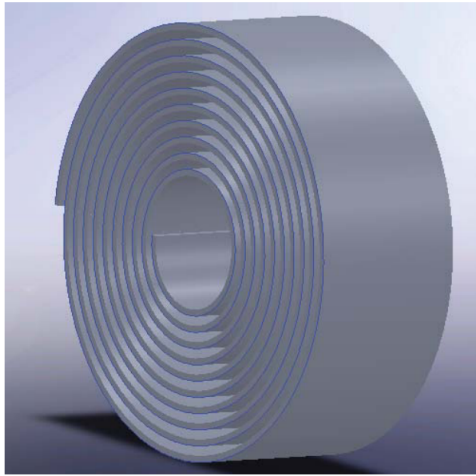


Figure 3.2: Block diagram of design process of air-core inductor

cause of the high magnetic flux density values in the inductor and they are easy to manufacture. Another reason is that copper foils can be used for winding. These foils both provide heat dissipation and reduce resistance. Figure 3.3 shows that copper foil (or sheet) and example of the copper layer.

Also, copper foil layers should be isolated electrically. To insulate layers, high voltage insulation papers are sprawled between copper foil layers. Figure 3.4 shows an example of insulation papers used in high voltage inductors and transformers.



(a) Inductor with copper layers[52]



(b) Copper foil [53]

Figure 3.3: Layers of inductor



Figure 3.4: Insulation papers used in Inductors [21]

3.2 Parameters of Air Core Inductors

Inductance, pressure, and resistance are the main design outputs of the high-energy air core inductor design process. A well-designed inductor should satisfy the inductance value with low resistance and should not be damaged by the lateral electromagnetic force, or with lateral pressure at the peak module output current. We face some trade-offs in the design of the air core inductor to find the optimum design. One design can have a low pressure but a high resistance, then others even they have the same inductance value. The input parameters of the inductor design are the physical dimensions and materials. Output and input parameters of the air-core inductors are discussed in the following text.

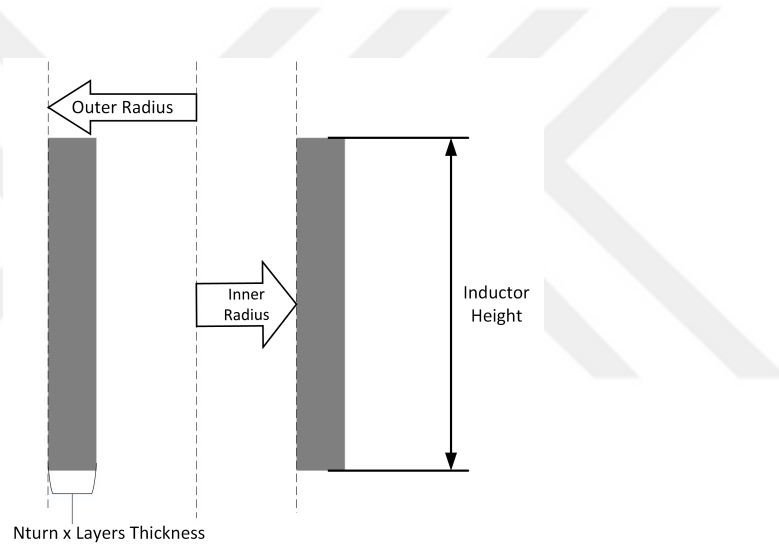


Figure 3.5: Design parameters of Inductor

3.2.1 Output Parameters

Inductance

Being the main design parameter, aim of the design algorithm is to obtain desired inductance value with small percentage error. Equation 31 is the basic formula for inductance of a coaxial inductor, where A is the coil area, h is the inductor height, μ

is the permeability and N is the number of turns as shown in Figure 3.5.

$$L = \frac{N^2 \mu A}{h} \quad (31)$$

Pressure

In high energy applications, electromagnetic force becomes very critical because it can cause damage on inductor. Lateral electromagnetic forces that are due to the Lorentz force are given in 32, they cause pressure on insulation layers and covered material in the radial direction.

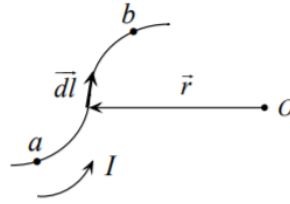


Figure 3.6: A current-carrying wire inside a static magnetic field [22]

$$\vec{F}_m = I \int d\vec{l} \vec{B}(\vec{r}) \quad (32)$$

In 32, F_m is the magnetic force, I is the current of the conductor, B is the external magnetic field density, l is the length of the conductor and r is the radial distance as shown in Figure 3.6. From the right-hand rule, the electromagnetic force is produced in radial direction.

To increase the mechanical robustness, the inductor is covered with polyurethane material and blank spaces are filled with epoxy resin [23]. Figure 3.7 shows inductor designs without faults. If pressure exceeds the maximum limits of these materials, the inductor may fail or even explode. Figures 3.9 and 3.8 show pressure-based failure in high energy air-core inductors in pulse power applications.

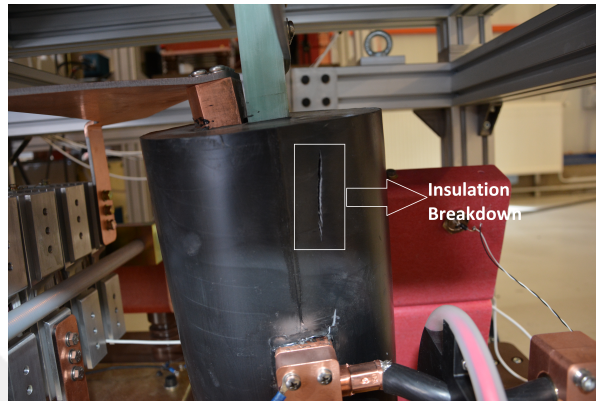


(a) Prototype 1



(b) Prototype 2

Figure 3.7: Inductor designs without any fault [23]



(a) Broken inductor 1



(b) Broken inductor 2

Figure 3.8: Damaged air-core inductor due to lateral force



(a) Short circuited inductor 1



(b) Short circuited inductor 2

Figure 3.9: Lateral electromagnetic force breaks isolation layer and leads short circuit

If copper foil layers were not used, it would be possible to improve the resistance and decrease the lateral electromagnetic force by changing the winding method in this type of coil. The Spider-web coil winding as shown in Figure 3.10 is one of them [24]. But it is not suitable for copper foil winding.

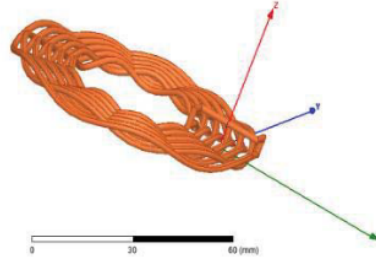


Figure 3.10: Spider-web winding coil design [24]

Resistance

In capacitive pulse power supplies, there are 3 types of resistances that are capacitor resistance, semiconductor resistances, and inductor resistance. The inductor resistance is higher than the others in general, so that module resistance depends on it mostly. Moreover, it is hard to change the resistance of semiconductors and capacitors. So that, module efficiency is affected by the changing of resistance of the inductor. Smaller inductor resistance is better for this application.

3.2.2 Input Parameters

Design parameter are obtained from 31 and shown in Figure 3.5. The equation includes the number of turns, coil area, and height variables. The effective area (A) of the inductor depends on the inner and outer radius. The outer radius is a summation of the inner radius and total copper and insulation layer thicknesses. The following variable parameters are used in the design algorithm.

- Inductor Height
- Number of Turn
- Copper Layer Thickness
- Insulation Layer Thickness

- Inner Radius
- Outer Radius

Copper and insulation layer thicknesses are taken constant, whereas height, turn number, and inner radius are varied parameters and the outer radius is calculated according to the inner radius of the inductor. Example of the copper sheets are shown in Figure 3.3.

3.3 Capacitive PPS Parameters' Selection and Calculating Inductance Value

Capacitive PPS parameters are dependent on each other so that some of these should be specified at the beginning of the algorithm, and they become initial values of the design loop. These initial values are the charging voltage and module energy.

Charging voltage is determined according to DC power supply capacity and maximum capacitor voltage. In this design algorithm, charging voltage is specified as *6500V*.

Module energy is specified as *100kJ*.

By using these, semiconductors are chosen, and also capacitance and inductance values are calculated.

Capacitance is calculated from capacitor energy equation given in (33). By using this equation, capacitance is found as *4.7mF*.

$$E_{module} = E_{capacitor} = \frac{1}{2} C_{capacitor} V_{charge}^2 \quad (33)$$

Both diode's and thyristor's voltage levels should be 3/2 times bigger than the charging voltage. To satisfy this condition, semiconductors can be connected in series.

Also, maximum module current should not be exceeded semiconductors surge current values. This value is determined initially and semiconductors are selected for this maximum current. For this design, maximum current is specified as $100kA$ and also forward voltage is specified as $V_f = 2 * 1.2V = 2.4 V$. This value is taken from data sheets of similar semiconductors used in similar systems.

Inductance value of the shaping inductor is the starting point of the algorithm. It is calculated from the energy equations of the inductor and capacitor. In ideal conditions, all of the energy stored in capacitor transfers to the inductor as electromagnetic energy. This condition is similar to short circuit tests of PPS modules. If resistances are ignored, maximum current can be found. If the design is made accordingly, it can be guaranteed that the semiconductor's current limit will not be exceeded to be in a safe region.

$$E_{inductor} = \frac{1}{2} L_{inductor} I_{max}^2 \quad (34)$$

$$E_{capacitor} = E_{inductor} \quad (35)$$

$$\frac{1}{2} C_{capacitor} V_{charge}^2 = \frac{1}{2} L_{inductor} I_{max}^2 \quad (36)$$

$$L_{inductor} = C_{capacitor} \left(\frac{V_{charge}}{I_{max}} \right)^2 \quad (37)$$

By using (37), inductance value is found as $20uH$. After this calculation, we have to verify this result because parasitic inductance, capacitance, and resistance of components are ignored to simplify the calculation. So that, PPS is modeled in Simulink to verify the found inductance value. This model can be seen in Figure 3.11. Simulink model includes parasitic components like inductance of diodes (L_d), thyristors (L_{scr}) and capacitors (L_c); inductor resistance for high (RI_{HF}) and low (RI_{LF}) frequencies. These resistances are the average value of inductor for similar inductor design.

All simulations are made with a short-circuited load at this work. This means there is only short circuit cable inductance (L_{cable}) and resistance (R_{cable}) as the load. Exemplary simulation results fort PPS currents are given in Figure 3.12. If the current is

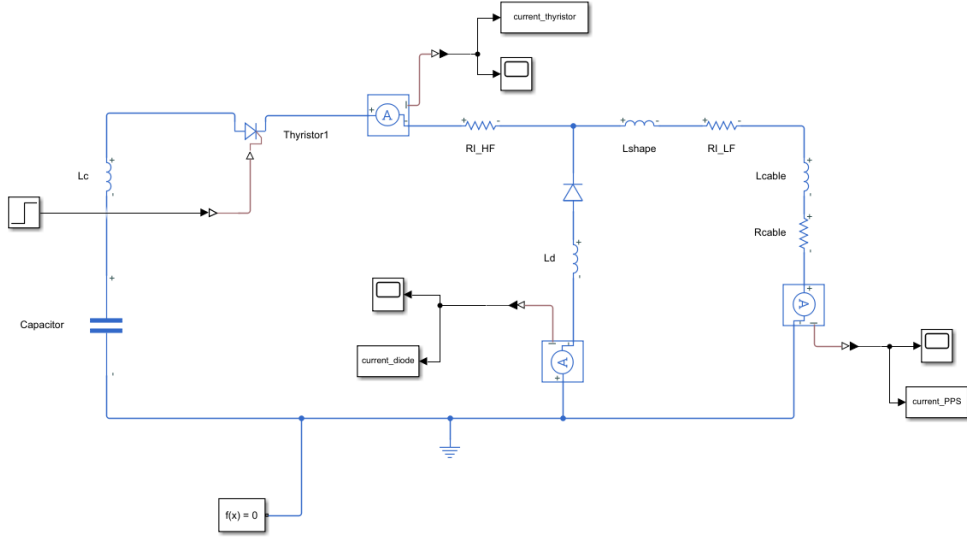


Figure 3.11: Simulink Circuit of PPS model

higher than the maximum limits of semiconductors, the calculated inductance value is increased five percent and re-simulated until a suitable L value is found.

Moreover, resonant frequency of the PPS module LC circuit could be calculated as 520Hz by using 38 [54]. In this calculation, parasitic capacitance and inductance values were not taken into account.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (38)$$

In PPS modules, the thyristor prevents current flowing in the opposite direction to the capacitor, and therefore no resonance or oscillation is observed. Resonant frequency calculation for CPPS modules is valid if there is no thyristor in the circuit.

3.4 2D FEM Simulations for Different Design Parameters

Any inductance value could be obtained by changing the geometry, but each design can have some pros and cons. So that every design output should be examined separately to reach the optimized design. To find the optimum coaxial high-energy air core inductor, a lot of designs are simulated with the finite element method. We have

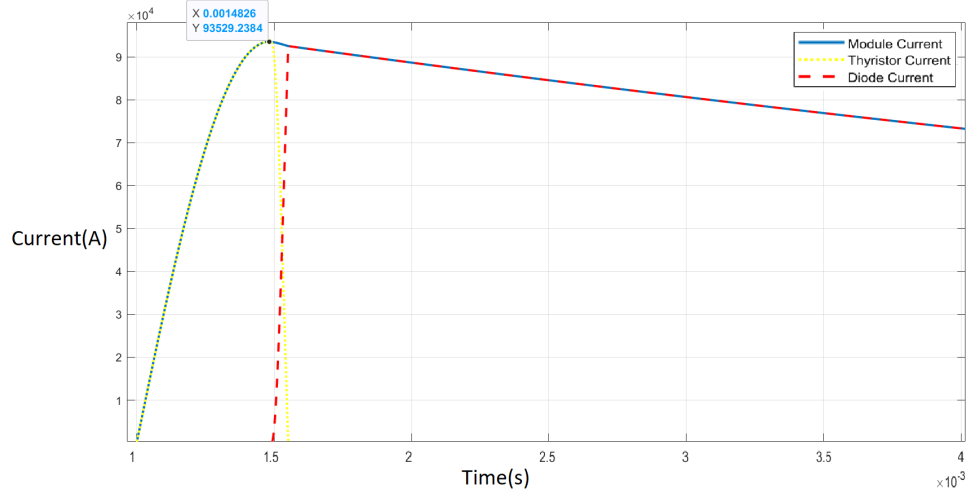


Figure 3.12: Load current of module, thyristor's current and diode's current

to simulate all of the designs because there is no exact mathematical equation for an air-core inductor as the distribution of magnetic field lines could not be estimated analytically. In subsection 2.1.2.1, some equations are given. Results of these equations are compared with the finite element and experimental results for an existing inductor in Table 3.1. The closest result to the measurements is obtained with FEM analysis. Results of some of the previously given equations can also give acceptable results.

Table 3.1: Comparison of methods for a produced inductor with $N = 16.5$, inductor height = 30cm, inner diameter = 15cm, outer diameter = 22.75cm

Method	Inductance	Error
Experimental:	19.8uH	%0
FEM:	20.7uH	%4.5
Formula (22):	21.1uH	%6.5
Formula (23):	22.8uH	%15
Formula (24):	21.75uH	%9.8
Formula (31):	31.7uH	%60

The main reason for differences between analytical calculations and FEM analysis is the unknown effective length of the air-core of inductor. Analytical inductance calculation of an iron core inductor is simpler since the most of the energy is stored in the air-gap from which the effective length can be estimated easily. However,

in an air-cored inductor, energy is stored inside the coil and right next to the coil, too. To design this kind of an inductor or simply a coil, finite element method-based calculation is crucial.

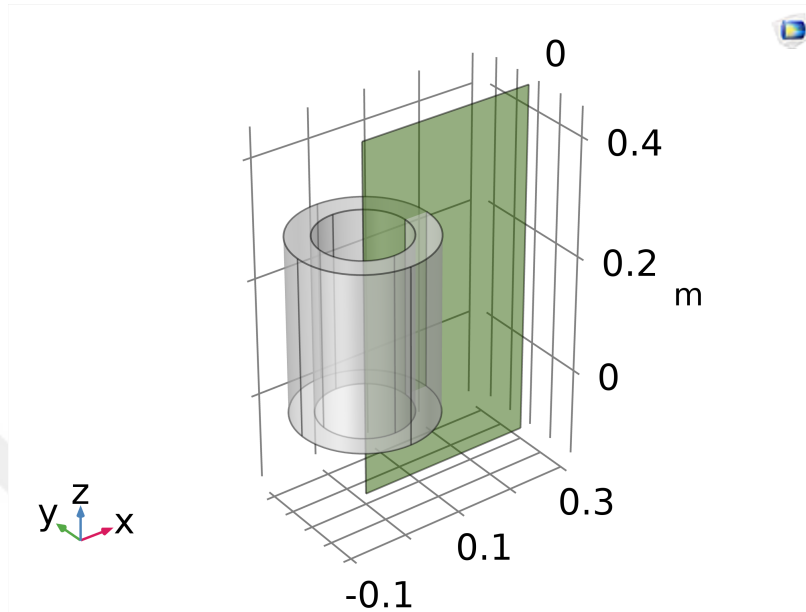


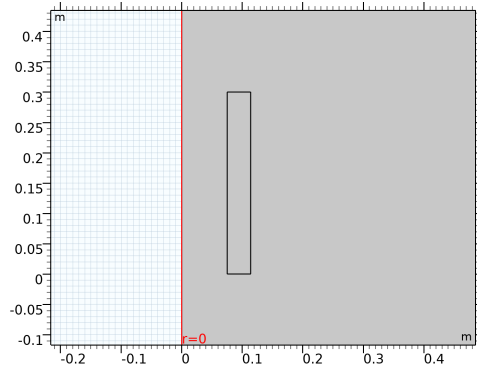
Figure 3.13: 3D model view of Inductor and cut-line (green plane) for 2D simulation

Simulations for inductor parameters are made in cylindrical coordinate system around z-axes. Cut-line of the 3D model for 2D analysis shown in Figure 3.13. Two 2D FEA simulation models with cylindrical symmetry around z-axes are used in this part. These can be seen in Figure 3.14. By using the first of them, cross-section of the inductor is simulated to find inductance and pressure. In the second model, one copper layer cross-section of the inductor is modeled to obtain resistance.

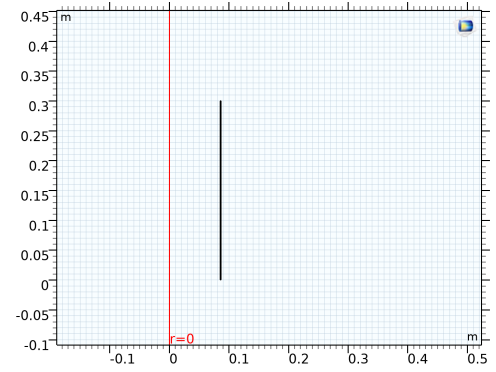
Figures 3.15a and 3.15b show magnetic flux density and magnetic field lines. We can see that the magnetic field density is also high inside the coil as well as at the top and bottom of outer parts of the inductor.

Figure 3.16 shows the density of magnetic flux at the center-lines of the inductor. These lines are depicted in Figure 3.15a as vertical and horizontal cut lines. This kind of distribution makes the inductance analytical formalization hard.

It is also important to mention the very high flux density values up to 6T in the inductor. This shows why an air-core inductor must be used as well as why we need to be



(a) 2D Inductor Simulation Drawing for Inductance and Pressure



(b) 2D Copper Layer Simulation Drawing for Resistance

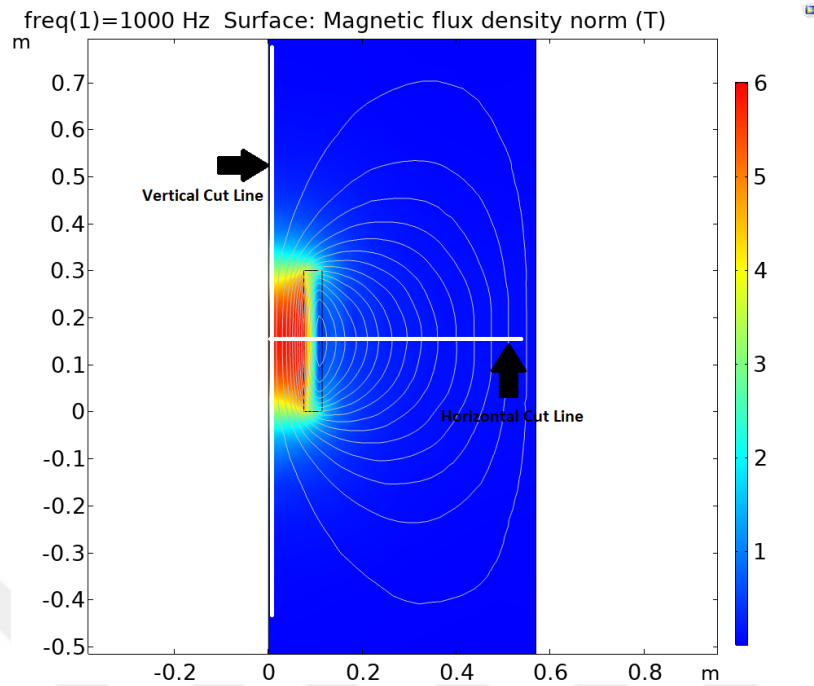
Figure 3.14: FEA models in Comsol

careful with magnetic field linking the inductors of the other modules.

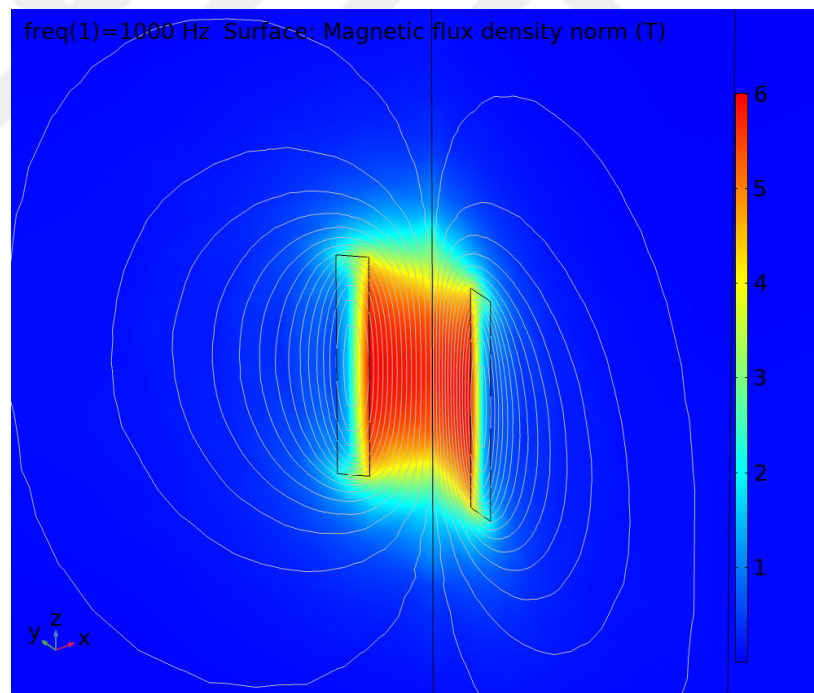
To find the best inductor parameters, their combinations are simulated with Comsol 2D for inductance, pressure, and resistance as stated earlier. Intervals of parameters are shown in Table 3.2. These sweep intervals are specified based on the calculated inductance value that is found in previously to decrease the simulation time. According to desired inductance value, they will change. Due to volume specifications, output diameter and inductor height are limited to 30cm in the algorithm, so that bigger inductors are eliminated.

Table 3.2: Sweep intervals of input parameters to design a 20uH inductor

Parameter	Start	Stop	Step
Inner Radius	5cm	12cm	1cm
Number of Turn	10	25	1
Height of Inductor	10cm	30cm	2cm

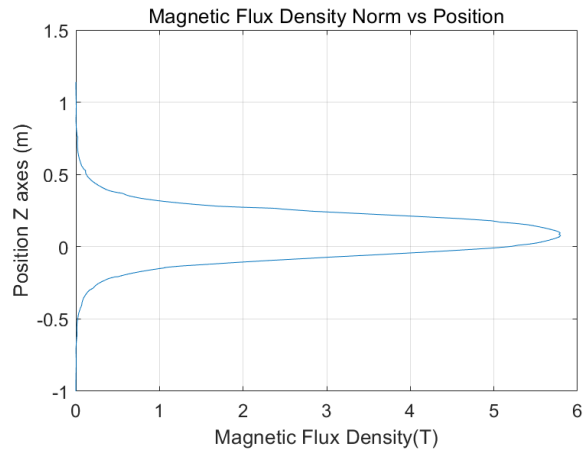


(a) View with cut-lines for 1D graph

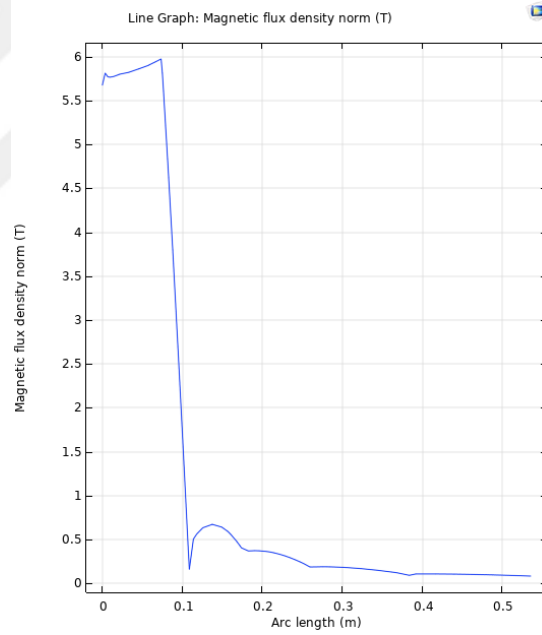


(b) View with 2D cross-section

Figure 3.15: 2D FEA results for magnetic field density and magnetic flux lines of air core inductor



(a) Vertical cut line



(b) Horizontal cut line

Figure 3.16: Magnetic flux density distributions

All of the combinations in Table 3.2 are simulated which makes in total 1408 inductors. Result of these simulations are presented in the following subsections

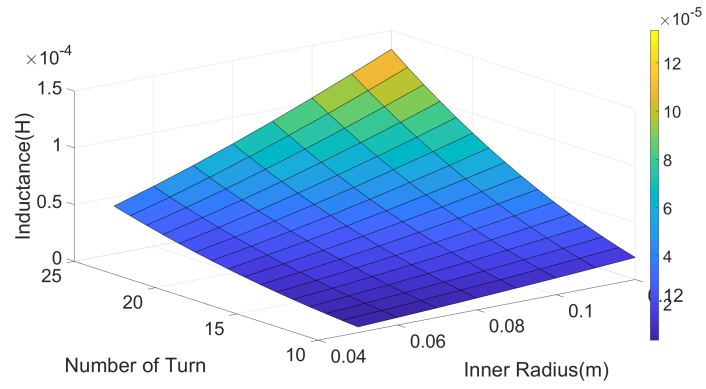
3.4.1 Simulations Results for Inductance and Pressure

All of these simulations in this subsection are made in frequency domain at 1000kHz. Although frequency does not change the inductance value significantly, an AC excitation was required for the solver setup.

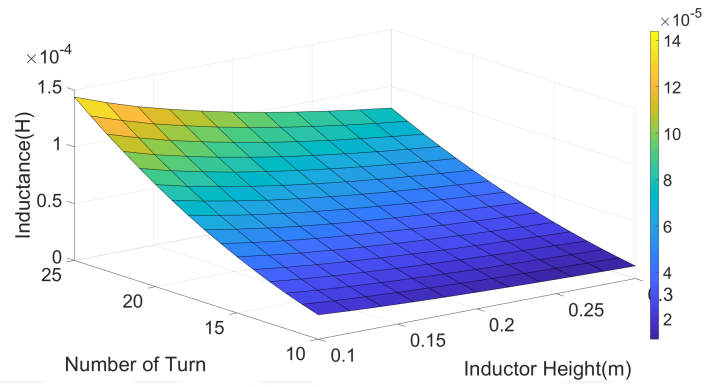
Relationships between input parameters and inductance are showed in Figure 3.17. When the inner radius and number of turns increase and inductor height decreases, inductance increases. With the help of these graphics, dimensions of inductors with a required inductance can be determined. However, we need to calculate the lateral force on the inductor surface and the resistance to be able to come up to a decision.

At the same simulation setup, electromagnetic Lorentz force could be obtained. Figure 3.18 shows produced force density distribution in N/m^3 under the specified operating current that is 100kA. The lateral pressure on the outer shell of the inductor is calculated by integrating this force density in the lateral section of the inductor winding. After calculating the lateral pressure on the inductor surface, the average of these values is output by the algorithm.

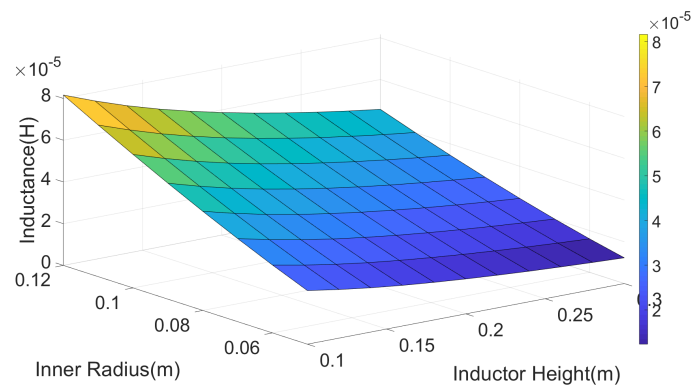
Relationships between input parameters and average surface pressure are given in Figure 3.19. When inner radius and inductor height increase, the number of turns decreases and the lateral pressure decreases.



(a) Inner radius and number of turns (Height = 0.2m)



(b) Inductor height and number of turns ($r_{inner} = 0.1\text{m}$)



(c) Inner radius and Inductor height ($N_{turn} = 17$)

Figure 3.17: Inductance vs input parameters graphs

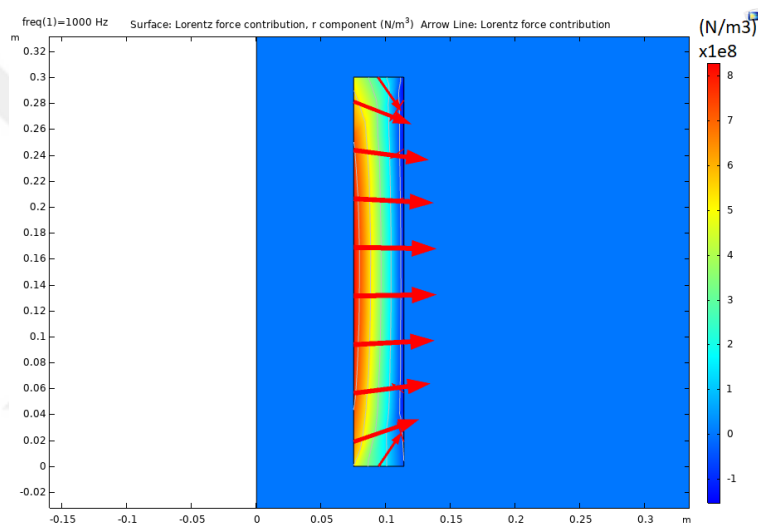
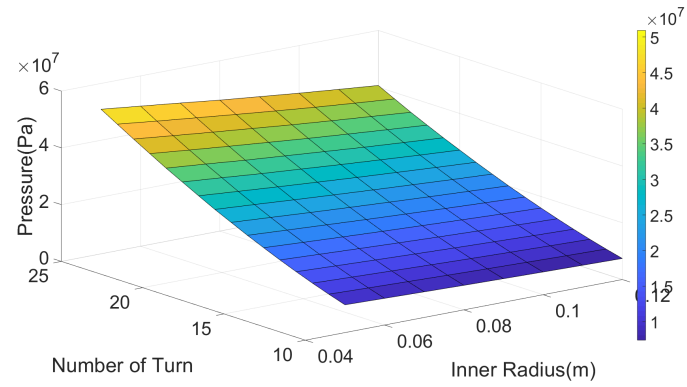
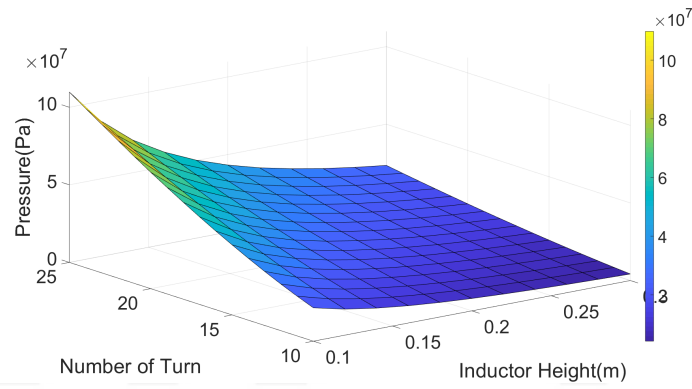


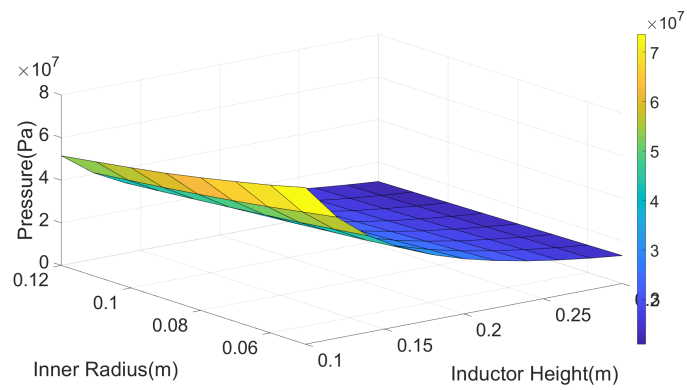
Figure 3.18: Radial electromagnetic force density in N/m³ and lines



(a) Inner radius and number of turns (Height = 0.2m)



(b) Inductor height and number of turns (inner radius = 0.1m)



(c) Inner radius and inductor height (Nturn = 17)

Figure 3.19: Average surface pressure vs input parameters graphs

3.4.2 Simulations for AC Resistance

The simulated current waveforms in Figure 3.12 shows that rising and falling frequencies of current are different from each other. And also current change rapidly so that we can not use DC resistance values. Moreover current waveforms depend on PPS circuit parameters as well as load rising and falling frequencies of the module. It is found out from the tests that rising frequency is higher than falling one in general. So that, the rising frequency is assumed to be 1000Hz, falling one to be 500Hz. These values are not so critical since AC resistance is almost constant around these values for the used copper thicknesses that was 1.3mm. Skin depth of 3000Hz current is approximately 1.3mm for copper so that AC resistances of the copper layer are almost constant if the frequency smaller than this. Actually, copper thickness should be selected based on the expected frequencies. And also, the same estimation is made for all designs so there is no problem for any design under the 3000Hz excitation.

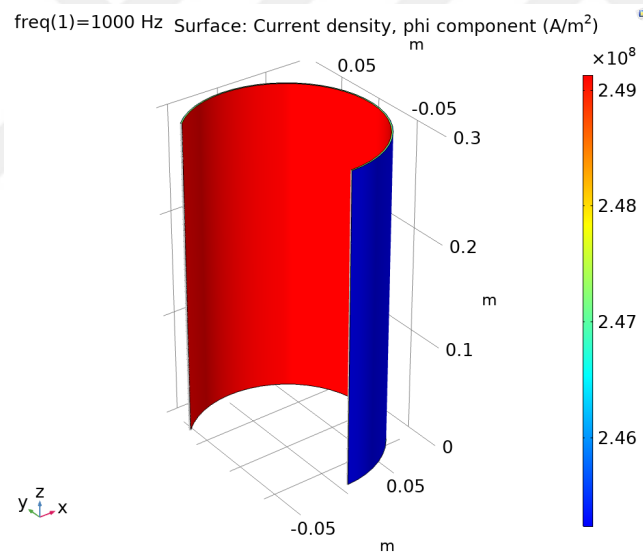


Figure 3.20: Current density graph at 100kA excitation at 1000Hz

Only one layer of the inductor is simulated at this part, from which the radius is the average of the inner and the outer radius. Then, calculated resistances are multiplied by the number of turns to get the inductor resistance. Due to the cylindrical winding shape current flows closer to the inner side as can be seen in Figures 3.20 and 3.21. Resistance changes due to this and skin effect. Proximity effect was not considered.

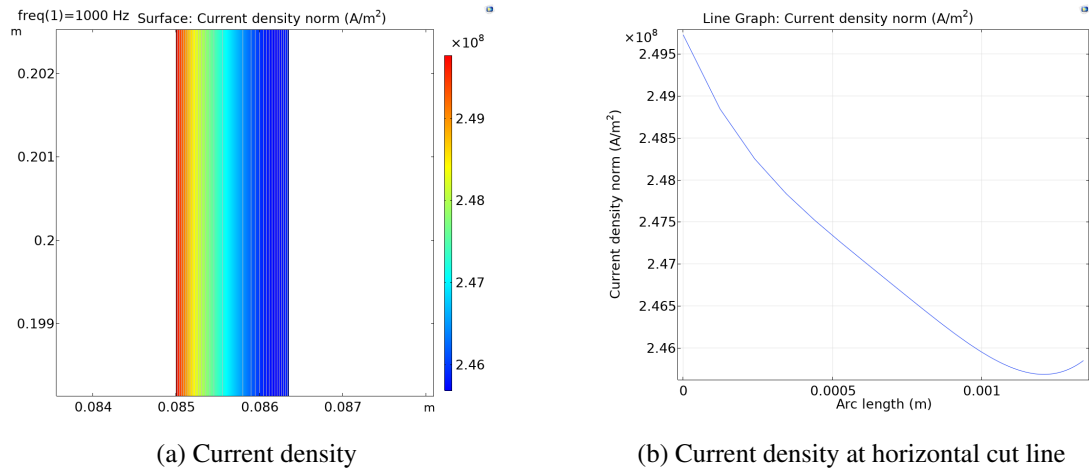


Figure 3.21: Current density of cylindrical shaped copper layer

3.5 Selection of Suitable Inductors

After all output parameters for the all 1408 inductors are calculated, firstly, the inductance values of all designs are checked, and if anyone of them is smaller than the desired value, they are eliminated. Because when the inductance is lower, the maximum current value is higher than the limits. Moreover, an error function is created to reduce the number of final designs to 30. Error function includes pressure error, inductance error, and resistance error values with %50, %30, and %20 contributions in final error, respectively. Pressure error and resistance errors are calculated according to the pressure and resistance averages of all designs, but the inductance error is calculated for the desired inductance value. And all error types are normalized then a total error is calculated. The smaller error is the better. Reference values of the resistances and the pressures are average of the all desing's, so that the percentage error could be negative. The percentage of pressure is higher because this is an operating critical value for each design that may lead to system failure. According to the mechanical analysis, the maximum compressive strength of the durability materials used for the inductor is about 50 MPA, but the strength varies according to the number of turns of this epoxy layer surrounding the coil. On the other hand, resistance values affect the efficiency of the system. All the designs are sorted according to their error. Table 3.3 shows the selected 30 inductor designs that can be used in placement

analysis.

Table 3.3: Selected inductor designs with output parameters and error values

#	$h_{ind}(cm)$	$r_{in}(cm)$	N_{turn}	$P(MPa)$	$L(uH)$	$r_{out}(cm)$	$R_{0.5kHz}(m\Omega)$	$R_{1kHz}(m\Omega)$	Error
1	30	12	12	5,66	21,89	14,82	0,4184	0,4188	-38,43
2	26	12	11	5,99	20,09	14,59	0,4387	0,4390	-36,95
3	24	12	11	6,77	21,16	14,59	0,4753	0,4756	-34,5
4	26	11	12	7,29	21,03	13,82	0,4470	0,4473	-34,42
5	28	10	13	7,79	20,39	13,06	0,4178	0,4182	-33,53
6	26	10	13	8,76	21,46	13,06	0,4500	0,4503	-29,91
7	28	9	14	9,23	20,27	12,29	0,4157	0,4160	-29,74
8	20	11	11	9,22	20,73	13,59	0,5276	0,5280	-26,24
9	18	12	10	8,66	20,68	14,35	0,5710	0,5715	-25,99
10	26	9	14	10,39	21,36	12,29	0,4477	0,4481	-25,95
11	30	8	16	10,89	21,53	11,76	0,4118	0,4121	-25,76
12	22	10	12	9,76	20,24	12,82	0,4859	0,4863	-25,7
13	26	8	15	12,18	20,71	11,53	0,4402	0,4405	-21,87
14	30	7	17	12,51	20,15	11	0,3987	0,3990	-21,77
15	22	9	13	11,76	20,4	12,06	0,4859	0,4863	-20,8
16	20	10	12	11,28	21,5	12,82	0,5345	0,5349	-20,21
17	28	7	17	14,02	21,21	11	0,4272	0,4275	-17,58
18	24	8	15	13,85	21,91	11,53	0,4768	0,4772	-15,18
19	22	8	14	13,98	20,01	11,29	0,4797	0,4801	-14,75
20	30	6	19	15,71	20,76	10,47	0,4080	0,4083	-14,06
21	20	9	13	13,6	21,71	12,06	0,5345	0,5349	-13,94
22	16	10	11	13,32	20,49	12,59	0,6062	0,6066	-12,42
23	14	11	10	12,91	20,85	13,35	0,6787	0,6792	-11,27
24	24	7	16	16,1	20,7	10,76	0,4630	0,4633	-10,91
25	20	8	14	16,21	21,33	11,29	0,5277	0,5281	-8,02
26	28	6	19	17,64	21,89	10,47	0,4371	0,4375	-6,94
27	26	6	18	18,09	20,4	10,23	0,4397	0,4400	-6,25
28	16	9	12	16,36	21,01	11,82	0,6099	0,6104	-5,03
29	30	5	21	19,25	20,49	9,94	0,4094	0,4097	-4,51
30	22	7	16	18,52	21,99	10,76	0,5051	0,5055	-1,97

In summary, the parameters of the inductors are found for the desired inductance value by targeting the minimum lateral forces and resistances. The mutual effects between inductors can be different for each inductor design and each placement con-

figurations. For this reason, the placement configurations of the designed inductors should be examined. These placement analyzes will be given and each of the inductors could give different placement distances as we will see in the next chapter.





CHAPTER 4

CPPS MODULES' INDUCTOR PLACEMENT ANALYSIS

To supply a high amount of pulsated energy, many of pulse power supply modules can be connected in parallel. Modules are placed bottom to bottom in a container as shown in Figure 4.1, where there are 16 slots for modules from which 13 are placed. Modules are placed as close as possible to each other to increase the energy density of the PPS.



Figure 4.1: Pulse power supply modules of EML System

There are 2 different CPPS module circuit topologies that are used in these applications as shown in Figure 4.2. Topology in the Figure 4.2a is used to produce pulse power in general but induced emf on the shaping inductors could lead unwanted critical faults. On the other hand, topology in the Figure 4.2b is not affected by the induced EMFs because diodes could not open when thyristors are off. In second topology, unlike the previous one, the lifetime of the thyristors decreases as the thyristors carry all the load current. In this thesis, the first topology (Figure 4.2a), placement of

these and electromagnetic analysis of these CPPS modules are examined.

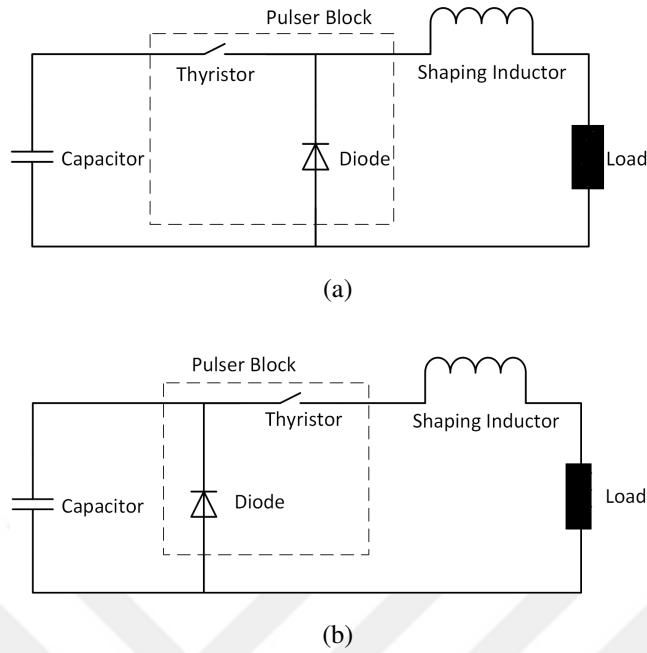


Figure 4.2: Capacitive PPS module topologies

As the previous results in Chapter 3 suggest, a high magnetic field is created by each shaping inductor. Although metal blocks and chassis decrease mutual electromagnetic effects between shaping inductors, some switching scenarios can result in a negative induced EMF on inductors of non-switched pulse power supply modules and diodes on these modules can start conducting. After that, if the thyristor of this non-switched module is triggered, the diode will be exposed to a very high reverse voltage and due to the diode failure the capacitor will be shorted as shown in Figure 4.3.

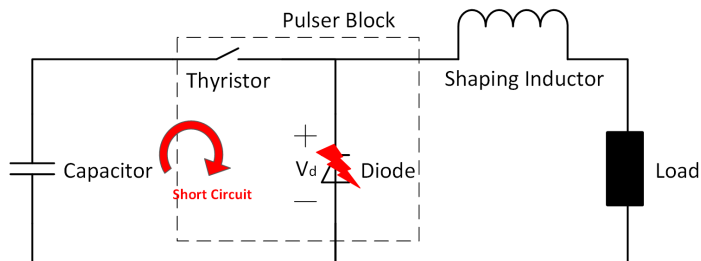


Figure 4.3: PPS module failure mechanism

This failure leads to diode failure and other mechanical defects due to high currents. Since, pulser is made by compressing thyristors and diodes in the same package, all pulser block becomes unusable after diode failure. Moreover, fixing the mechanical defects cause high labor costs. Figure 4.4 shows an example of the mechanical defect after diode failure.

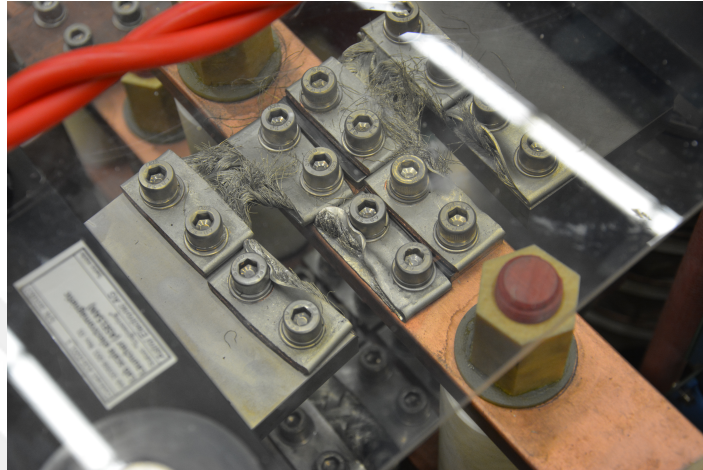


Figure 4.4: Example of mechanical defect after diode short circuit fault

To prevent diode short circuit faults in the EML systems, some protection circuits are used. For example, the voltage on the diode (V_d) is measured and if V_d is smaller than $-1.8V$, the firing trigger signal of the thyristor is cut. In Figure 4.5, the individual module currents from which 5 modules are triggered at 0ms and the rest of the modules are triggered one by one by 1 ms delays as well as the dashed blue lines shows the resultant current for a healthy operation whereas the dashed red line shows the resultant current if the module that supposed to be fired at 2ms has a failure or not activated due to protection. So that, the energy of the system decreases, and energies of the modules are discharged on the resistors, thus converted to the heat. Because of the decrease in the supply energy, speed of the projectile decreases, so the success rate of the operation. Moreover, the velocity of the armature and efficiency of the system decrease. Therefore, this study aims to develop design procedure that prevent these unwanted results.

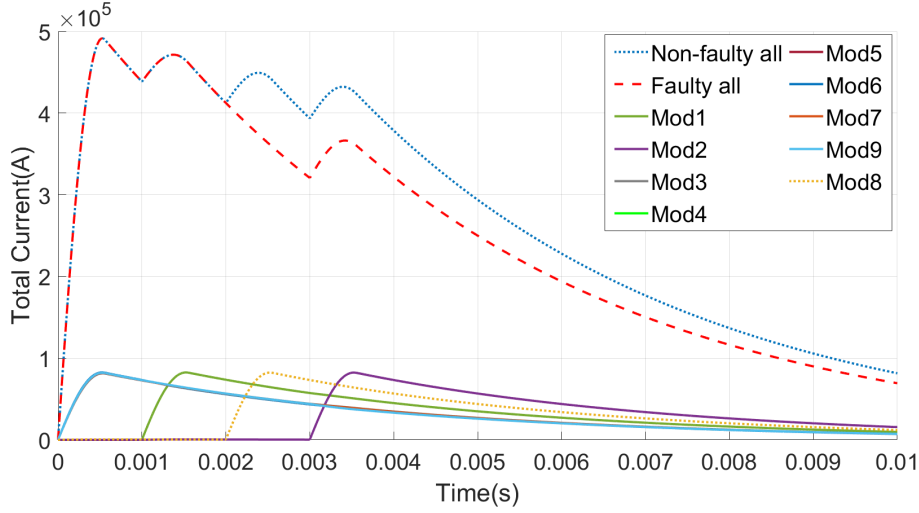


Figure 4.5: Current of the 9 modules with firing times at 5x0ms, 1x1ms, 1x2ms and 1x3ms; and resultant output currents when all modules are non-faulty and when the module triggered at 2ms is faulty

4.1 Method for Optimum Inductor Placement

To prevent these unexpected and unwanted results, it is proposed that the locations and orientations of the inductors can be designed systematically. In this section, the developed methodology for the placement of the module inductors is explained. A system with 9 modules that are placed in a 3 by 3 block is assumed as an example case as shown in Figure 4.6. Minimum horizontal and vertical distances between inductors are searched for each inductor placement combination by the algorithm.

Figure 4.7 shows a block diagram of the inductor placement procedure. Designed inductors in the previous chapter are used with 6 different placement orientations that will be introduced in the following part. For each combination, mutual inductance matrices between inductors are calculated with Comsol FEM software, and then these matrices are used for system level simulation of the module. The coupled inductor model is used for this in the Simulink simulation model. In this way, according to the firing sequence, we can check either the diode of any non-fired module opens or not. If the diode opens, the distances between inductors are increased by 15% and if not the distance decreased by 5%. Initial distances can be specified by some initial

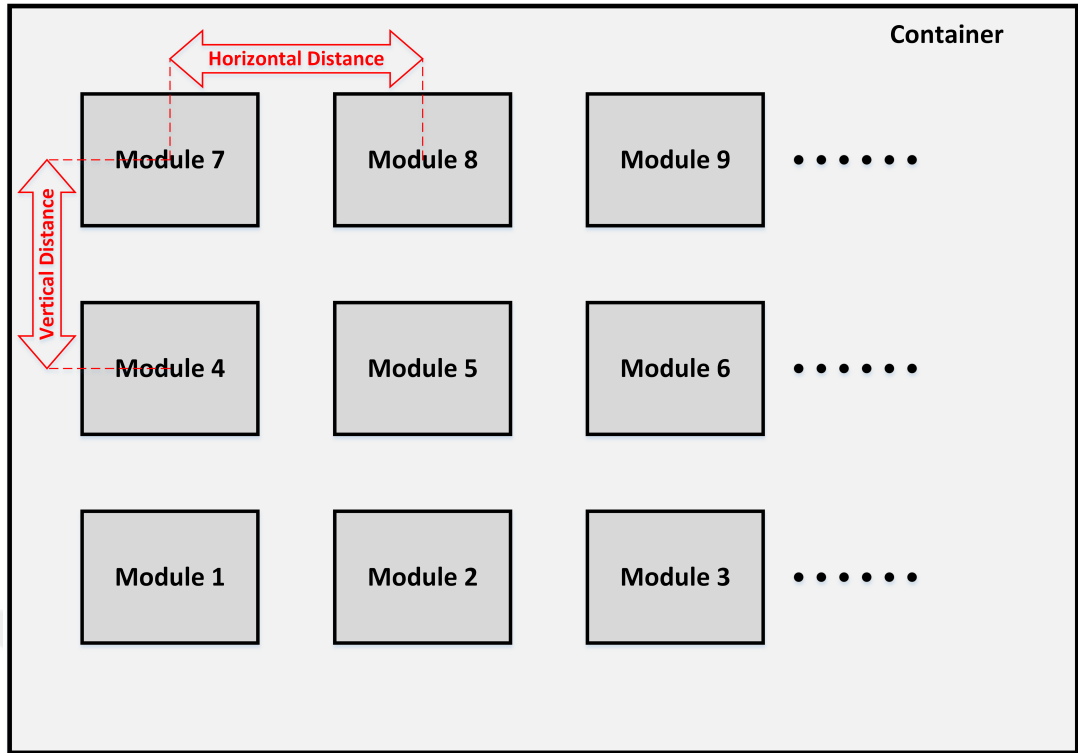


Figure 4.6: 3 by 3 module placement in the container

analysis and simulations or any constant values can be assigned. One important input to the design procedure is switching sequence of the modules. Switching sequence determines the activation time of the modules. It is almost impossible to find optimum and acceptable safe distances between inductors for any possible switching sequence because one of the diodes could be opened with a bad switching scenario. When the algorithm uses the worst case scenario, distances will be too wide, causing the system to be not suitable for a mobile application. To prevent this, a method of 'Worst of Bests' switching scenario is proposed. It finds the worst scenarios among the best scenarios of probable switching states. This method will be explained in Subsection 4.1.4 in detail. Switching scenarios are decided with this algorithm and the system is designed to be safe and more compact. The steps of the proposed placement algorithm is explained in the following subsection.

4.1.1 Selected Placement Configurations

Basic inductor configuration types are used in the pulse power supplies in general. Basic means that all of the inductors have the same orientations like shown in Figure 4.8 where inductors are easily affecting each other and these could lead critical problems in this placement configurations. According to the proposed methodology that explained in this thesis, minimum safe distances of these placements are obtained and given in Table 4.11. The results suggest that the basic placement 1 needs an around 1,7m horizontal and around 1m vertical distances between inductors. The results for basic placement 2 is similar with vertical and horizontal distances swapped. So, the required minimum distances between inductors are too high so not practicable.

Table 4.1: Optimum distances for basic placements that shown in Figure 4.8 for two inductor types

Inductor	Placement	$h_{ind}(m)$	$r_{inner}(m)$	N_{turn}	$D_{horz}(m)$	$D_{vert}(m)$
1	<i>Basic1</i>	0,3	0,12	12	1,78	1,08
1	<i>Basic2</i>	0,3	0,12	12	1,05	1,78
2	<i>Basic1</i>	0,26	0,12	11	1,68	1,01
2	<i>Basic2</i>	0,26	0,12	11	1,08	1,74

To produce a safe and smaller energy system, different placement configurations should be generated. So, configurations to be used in the main algorithm are specified considering a reduced mutual couplings effects and induced EMFs. Figures 4.9 shows the used placements configurations in the algorithm which are selected after pre-evaluations. In the methodology, any placement configuration can be added easily and the number of placement configurations can be increased.

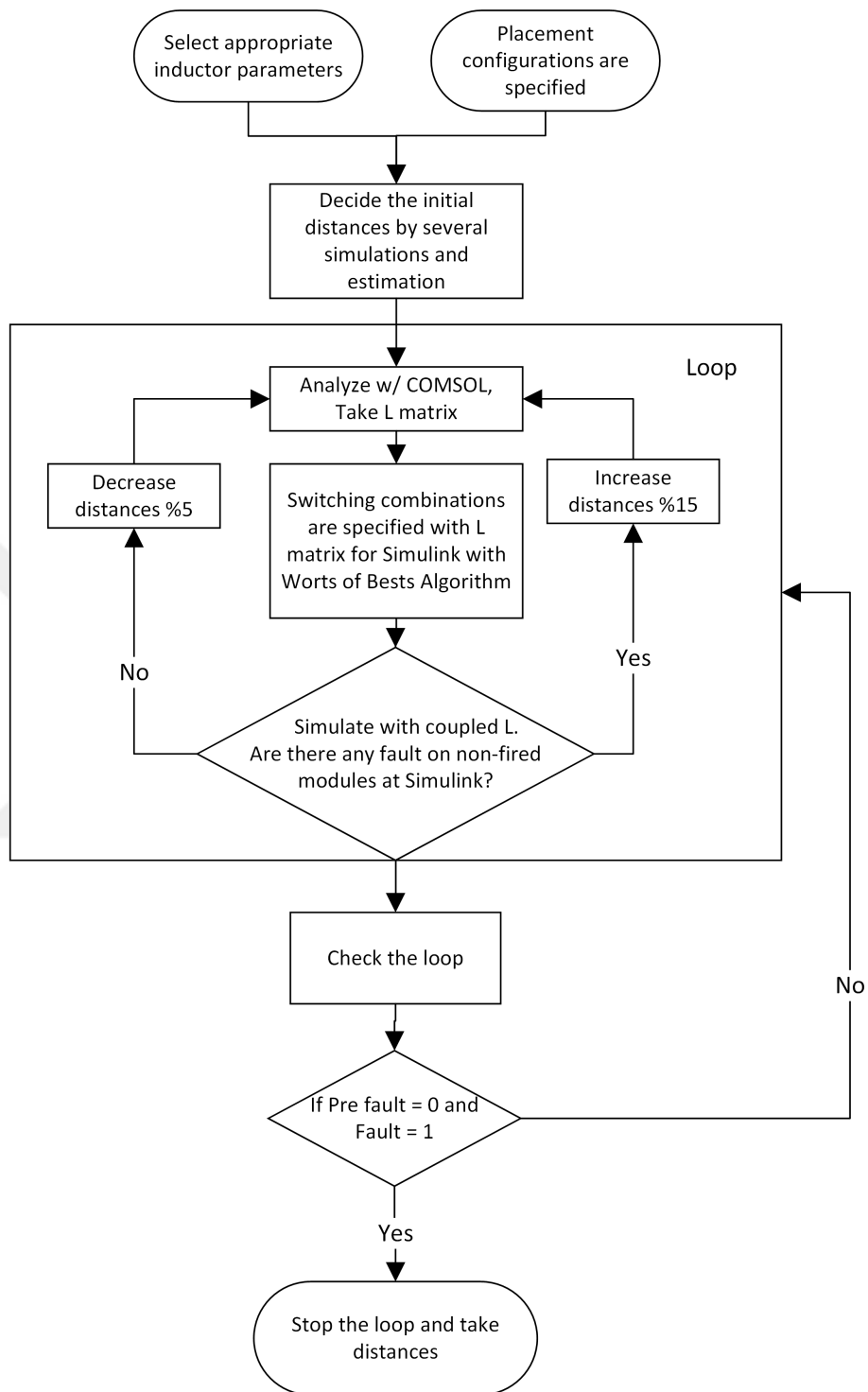
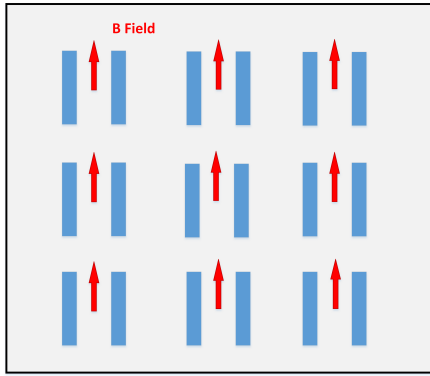
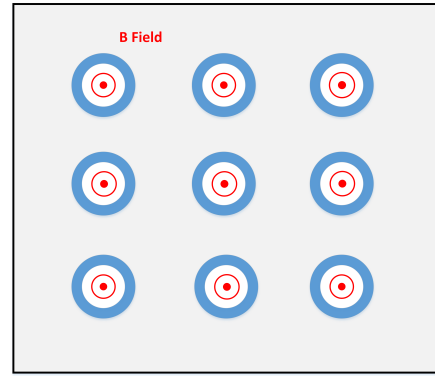


Figure 4.7: Block diagram of the placement analysis algorithm

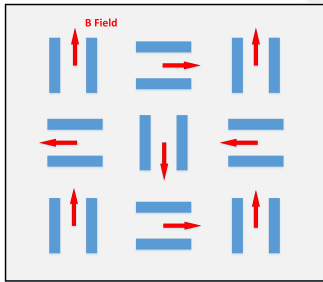


(a) Basic placement 1

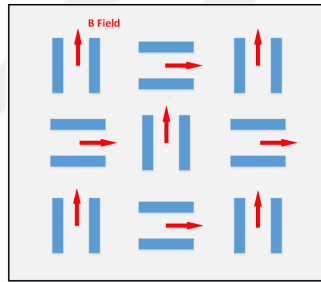


(b) Basic placement 2

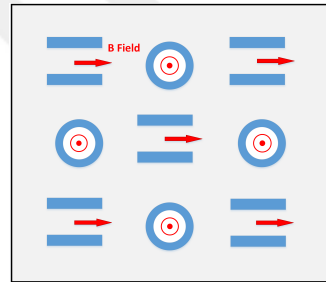
Figure 4.8: Basic placement configurations



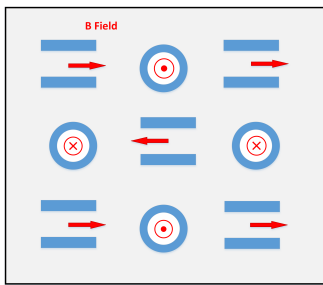
(a) 1st



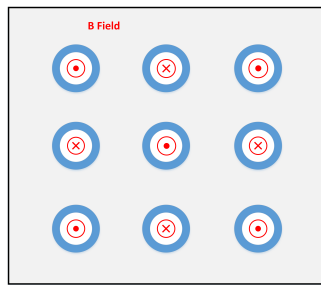
(b) 2nd



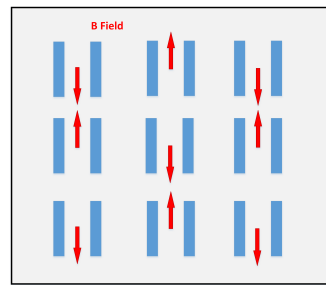
(c) 3rd



(d) 4th



(e) 5th



(f) 6th

Figure 4.9: Placement configurations used in the algorithm

4.1.2 Calculating Mutual Inductance Matrices

As Figure 4.6 shows, modules are stacked side by side and one on top of the other. To make reliable simulations, the mutual magnetic coupling effects should not be ignored. Inductance matrix is used at the mutual inductance component of the Simulink model. Therefore, inductance matrix of the shaping inductors are calculated. The components of the mutual inductance matrix for a 9 module configuration is given in Table 4.2, where self-inductances are shown by L_{xx} and mutual inductances by M_{xy} .

Table 4.2: Mutual inductance matrix

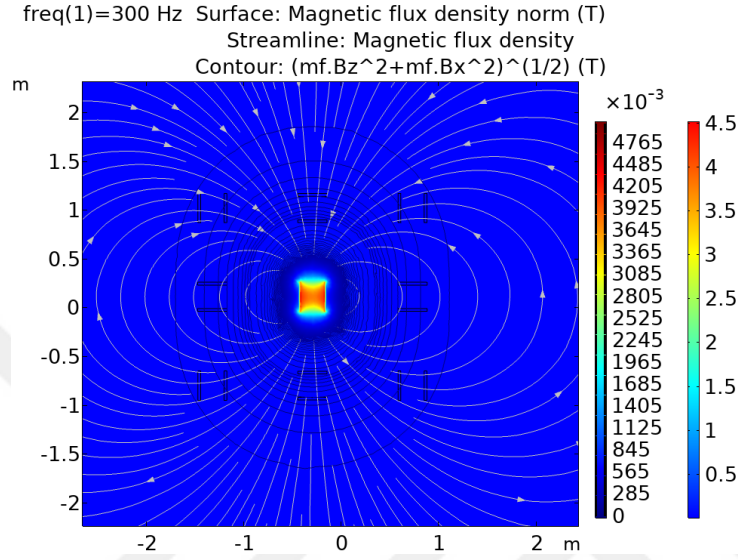
L_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	M_{17}	M_{18}	M_{19}
M_{21}	L_{22}	M_{23}	M_{24}	M_{25}	M_{26}	M_{27}	M_{28}	M_{29}
M_{31}	M_{32}	L_{33}	M_{34}	M_{35}	M_{36}	M_{37}	M_{38}	M_{39}
M_{41}	M_{42}	M_{43}	L_{44}	M_{45}	M_{46}	M_{47}	M_{48}	M_{49}
M_{51}	M_{52}	M_{53}	M_{54}	L_{55}	M_{56}	M_{57}	M_{58}	M_{59}
M_{61}	M_{62}	M_{63}	M_{64}	M_{65}	L_{66}	M_{67}	M_{68}	M_{69}
M_{71}	M_{72}	M_{73}	M_{74}	M_{75}	M_{76}	L_{77}	M_{78}	M_{79}
M_{81}	M_{82}	M_{83}	M_{84}	M_{85}	M_{86}	M_{87}	L_{88}	M_{89}
M_{91}	M_{92}	M_{93}	M_{94}	M_{95}	M_{96}	M_{97}	M_{98}	L_{99}

To obtain values in Table 4.2, eight 3D Comsol simulations are made for each combination of distances, orientations, and inductor types. For example, to get first-row, module 1 is excited and others are not, then all mutual inductance values in the first row are calculated from the induced EMF values. Self-inductances of all of the modules are identical and the matrix is symmetric according to $x=1-y$ axes so that 8 simulations give us the whole inductance matrix.

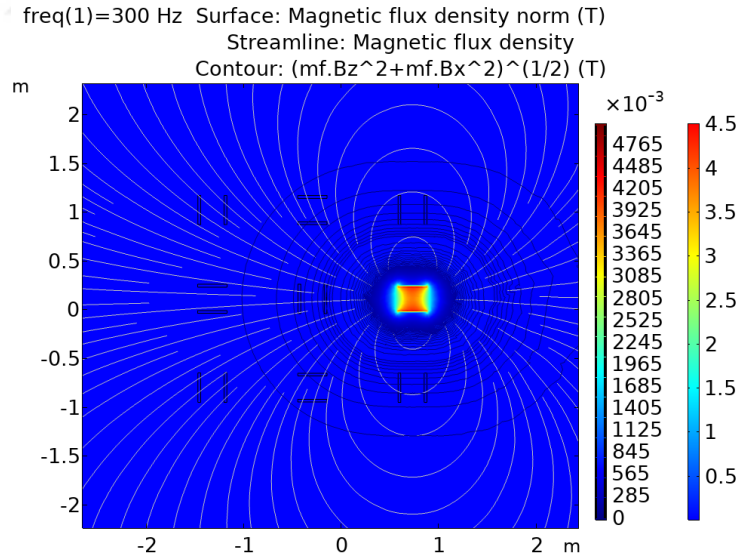
Figures 4.10 and 4.11 show examples for single module firing analyses. For this configuration, the magnetic field density at the center of the inductor is higher than 4.5T for 100kA current excitation. This flux density value is quite high.

Table 4.3: Parameters of the inductor used in the results shown in Figures 4.10 and 4.11

Inner Radius	Inductance Height	Nturn	Horizontal Dist.	Vertical Dist.
0.12m	0.3m	12	0.97m	0.91m

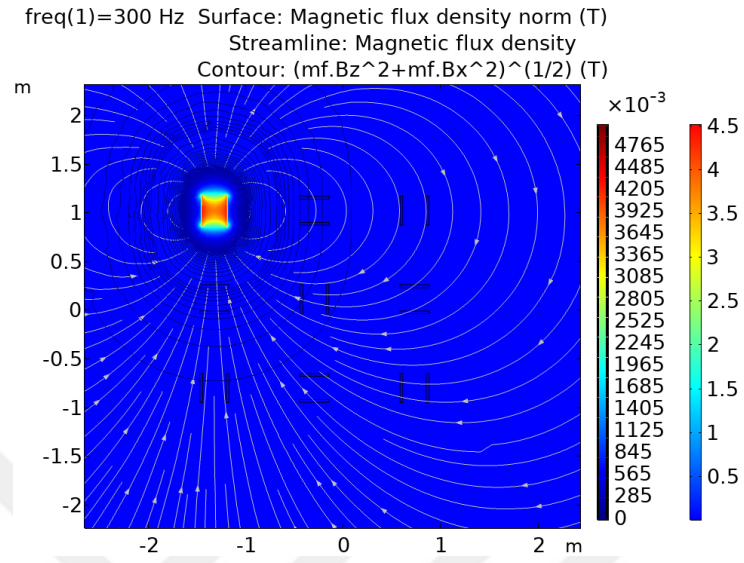


(a) 5th module fired

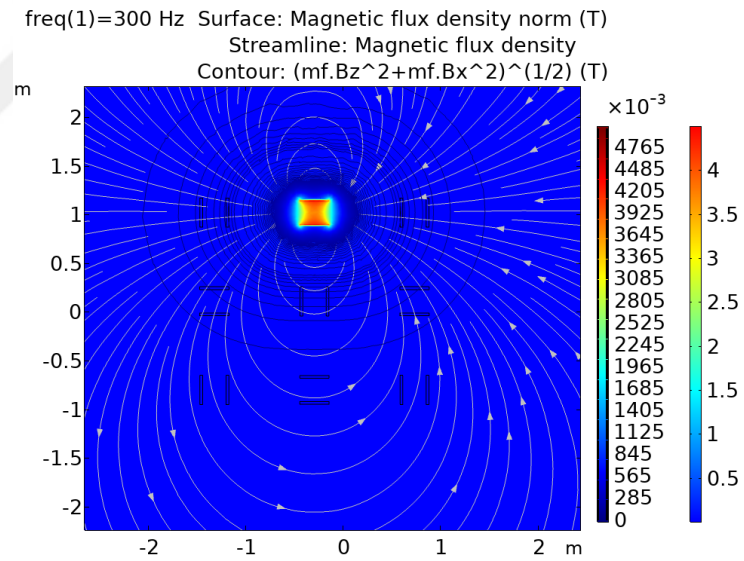


(b) 6th module fired

Figure 4.10: Magnetic field density distribution for 5th and 6th modules placed according to the 1st placement



(a) 7th Module Fired



(b) 8th Module Fired

Figure 4.11: Magnetic field density distribution for 7th and 8th modules placed according to the 1st placement

4.1.3 Determination of Initial Distances between Inductors

The design methodology needs initial distances for horizontal and vertical distance between modules. 2 methods could be used for this. Both methods give us similar computation times.

One of these methods is starting the algorithm from the same horizontal and vertical distances, for example, it could be 50cm. This method gives us the same horizontal and vertical distance values. But the volume of the system could be smaller if horizontal and vertical distances are different from each other. Also, the effect of horizontal and vertical distances on the mutual coupling between inductors could be different from each other. To obtain this ratio, a second method is generated. In the second method, induced EMF function according to vertical and horizontal distances is generated. EMF value is taken from Worst of Best switching scenarios, that will be detailed in next section, for each distance. This function is fitted with 10 different input configurations. Intervals of center to center distances are between 30cm and 140cm. For each distance combination, Simulink simulations are performed and modules are fired according to the output firing scenario of the Worst of Best algorithm. The worst EMF value in the non-fired modules of this scenario is used for mapping EMF values according to distances. Then surface graphs are obtained like Figure 4.12. Worst of Best algorithm is searched all of the firing combinations and for all number of module firing, then finds bests combinations for all number of firing sequences. And then EMF values of the worst ones are taken for the mapping algorithm. Meanwhile, there are not only 1 module EMF values mapping, it is not important which one is the worst in this step.

According to the semiconductors specifications, the optimum point is selected. Then algorithm starts from these distances. For example, if diodes open at 0.8V and 3 series diodes open 2.4V, V_d should be bigger than $-2.4V$. So that, the result of $f(x,y)$ is selected to be bigger than $-2.4V$ from the EMF map.

After this, the algorithm starts from these initial values and increases both distances by 15% on the next simulation loop if there is a fault on any diodes. And also the distances decrease by 5% if there is no fault. Finally, the algorithm stops if there is a no-fault in the previous simulation and there is a fault on the last simulation.

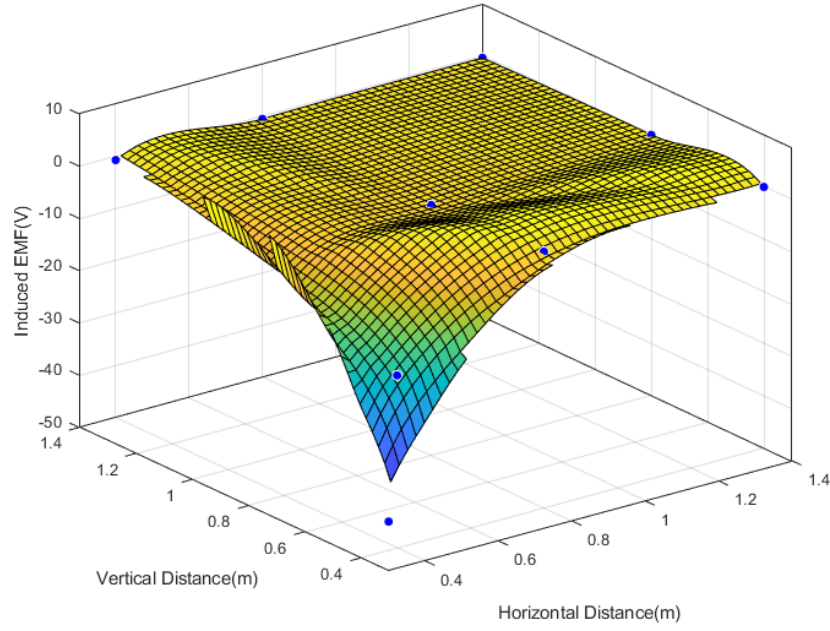


Figure 4.12: An example of mapping of EMF of the Worst of Bests switching outputs

4.1.4 Determination of Switching Scenarios of CPPS Modules

This is one of the most crucial steps of the algorithm. Since the switching sequence will change the module placements and it is computationally very costly to simulate all possible switching sequences in Simulink model, a simplified method for EMF estimation of inductors is used. Estimated induced EMF matrix is used for preliminary work of the algorithm. Induced voltage of any module is calculated with (41) in which the value of $d\mathbf{I}/dt$ calculated from Simulink simulation results presented in Chapter 3 is used.

$$\mathbf{V}_{ind} = \mathbf{L}_{ind} d\mathbf{I}/dt \quad (41)$$

When V_d is bigger than zero, diodes do not open. So that the positive value of the diode voltage is not dangerous for the system. Also, magnitudes of these positive values are not important. Placement configurations should be made for aiming this case by considering the firing sequence. In this work, we focused on the induced EMF due to both rising and falling edges of current but the frequency of rising edge is higher than falling for short circuit analyses and tests. Because of this reason, in

the analytical calculations, $d\mathbf{I} / dt$ value is taken from the rising edge. After getting mutual inductance matrix and $d\mathbf{I} / dt$ value, induced EMF values of each module for any fired module are calculated to estimate the voltage on the diodes.

To make the analysis, the switching times of modules should be defined. Modules could be switched in any combination. Following sequences could be examples for a 3 by 3 system with 9 modules configurations: 3 + 3 + 3, 1 + 2 + 2 + 4, 5 + 4, 1 + 1 + 1 + 1 + 1 + 2 + 1 + 1 and so on. But, neither best nor worst scenarios can be used. Because in real system, worst scenarios are not chosen and it is hard to find the best scenarios. Determination of fired modules is made by **Worsts of Bests** algorithm. This algorithm calculates the induced EMFs of all modules for each firing sequence, and the safest a firing scenarios of each firing count are found. The worst 3 scenarios of these 9 firing cases are taken and tested with Simulink. In summary, first the inductance matrix is calculated, then induced EMFs of the inductors for many switching sequences are estimated by using (41). After that only 3 scenarios are simulated by using Simulink model. If any fault is observed on diodes with these 3 scenarios, distances are arranged to prevent the fault. The proposed algorithm decreases the analysis time.

4.1.5 Comparison of Placement Configurations

Each placement configuration has a different magnetic flux density path. Change of the path causes different induced EMF values on the shaping inductors. In this part, magnetic field density distribution and inductance matrices of placement configurations at 50cm horizontal and vertical distances are compared.

According to the distances, the polarization of some mutual inductance values could change. Because magnetic flux path changes and this causes changing of the z component (according to the inductor) direction of magnetic flux. So, the linear relationship of mutual inductances and distances is not observed. Also at some placement configurations, smaller distances are safer than values that are a little higher. In Tables 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, the mutual inductance values they are negative and higher than 20nH in magnitude are marked red. If a box is red, it means that if one of the

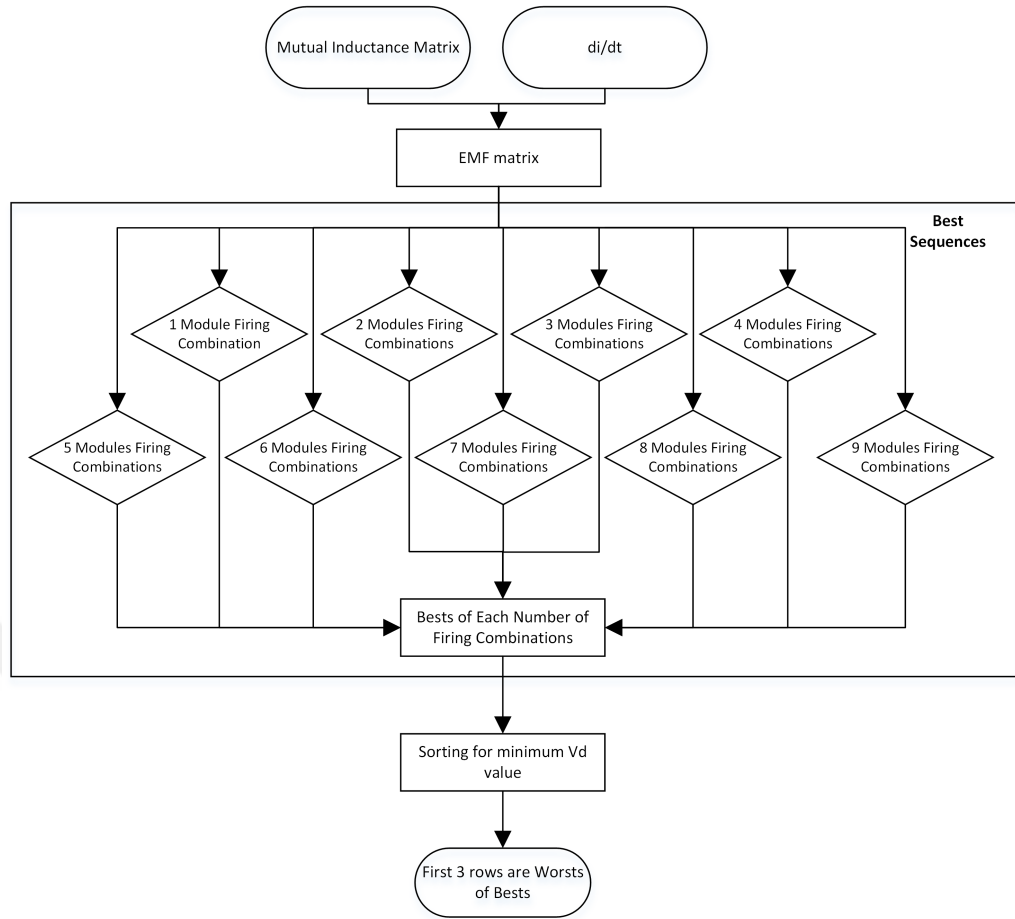


Figure 4.13: Flowchart of the Worst of Bests algorithm

corresponding inductors is fired, the other one will see a negative induced voltage higher than 2.4V in magnitude. So these modules can be activated at the same time. The configuration will be better if there are less red boxes.

When the given inductance matrices are studied, placement 6 can be found to be the worst configuration, because there are very critical coupling values. Negative inductance values are dangerous for freewheeling diodes. Therefore, 2nd and 3rd placement configurations are better than other configurations. In the EML systems, this kind of configuration will be more reliable.

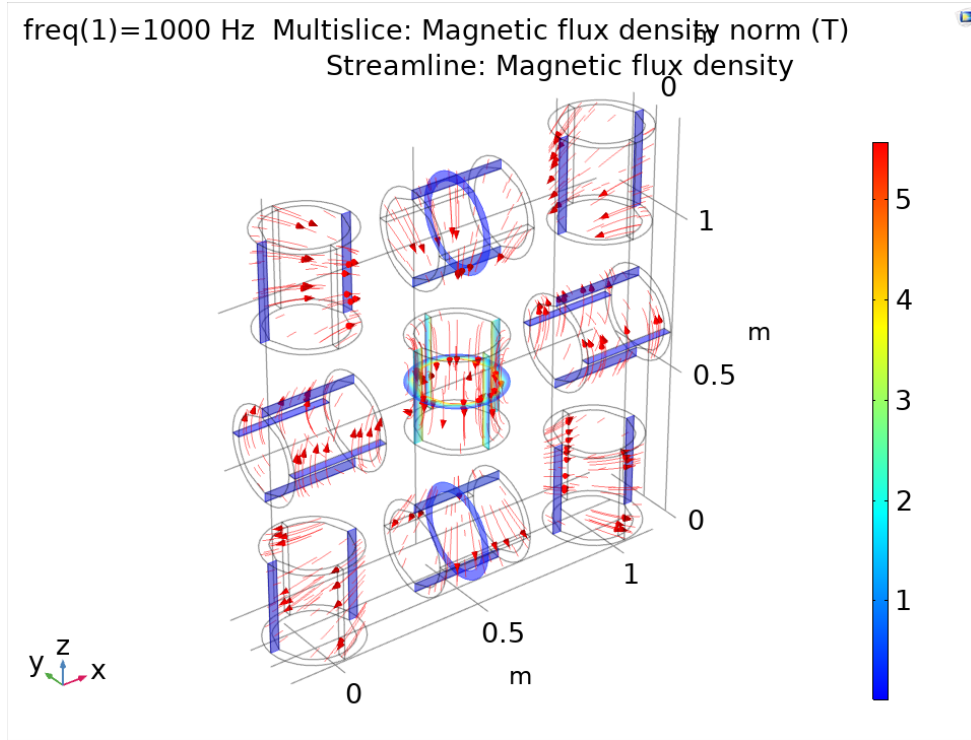


Figure 4.14: Magnetic flux density distribution of 1st placement with 0.5m x 0.5m distances

Table 4.4: Inductance matrix of placement 1 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	-4, 76n	-45, 01n	-0, 85n	-54, 88n	-39, 26n	93, 19n	39, 49n	6, 89n
2	-4, 76n	21, 8u	-0, 13n	-55, 82n	0, 09n	-55, 77n	-39, 40n	-45, 40n	39, 40n
3	-45, 01n	-0, 13n	21, 8u	39, 43n	-55, 79n	0, 13n	7, 02n	-39, 39n	93, 06n
4	-0, 85n	-55, 82n	39, 43n	21, 8u	-0, 36n	94, 28n	-0, 14n	-55, 85n	-39, 36n
5	-54, 88n	0, 09n	-55, 79n	-0, 36n	21, 8u	0, 27n	-55, 82n	-0, 19n	-55, 63n
6	-39, 26n	-55, 77n	0, 13n	94, 28n	0, 27n	21, 8u	39, 43n	-55, 76n	-0, 85n
7	93, 19n	-39, 40n	7, 02n	-0, 14n	-55, 82n	39, 43n	21, 8u	0, 12n	-45, 01n
8	39, 49n	-45, 40n	-39, 39n	-55, 85n	-0, 19n	-55, 76n	0, 12n	21, 8u	-0, 01n
9	6, 89n	39, 40n	93, 06n	-39, 36n	-55, 63n	-0, 85n	-45, 01n	-0, 01n	21, 8u

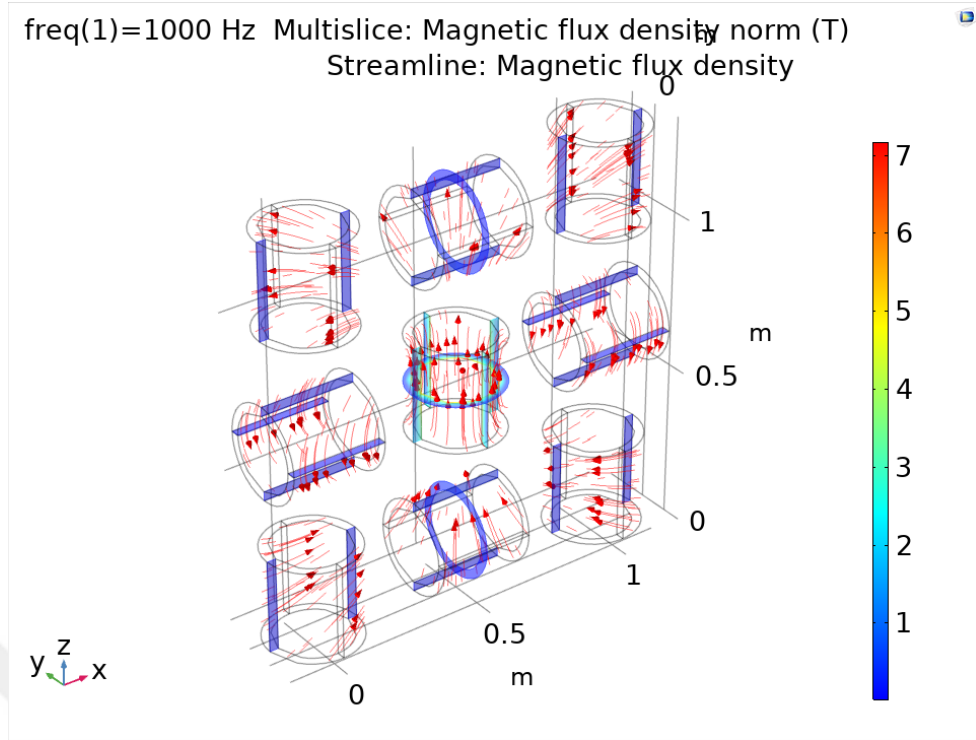


Figure 4.15: Magnetic flux density distribution of 2nd placement with 0.5m x 0.5m distances

Table 4.5: Inductance matrix of placement 2 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	-3, 58n	-44, 99n	0, 39n	55, 11n	39, 35n	93, 22n	39, 46n	6, 95n
2	-3, 58n	21, 8u	-0, 16n	55, 78n	0, 54n	55, 81n	-39, 40n	-45, 40n	39, 40n
3	-44, 99n	-0, 16n	21, 8u	-39, 43n	56, 50n	0, 16n	7, 02n	-39, 39n	93, 06n
4	0, 39n	55, 78n	-39, 43n	21, 8u	0, 08n	94, 28n	-0, 17n	55, 81n	39, 37n
5	55, 11n	0, 54n	56, 50n	0, 08n	21, 8u	-4, 34n	56, 00n	0, 86n	54, 87n
6	39, 35n	55, 81n	0, 16n	94, 28n	-4, 34n	21, 8u	-39, 43n	55, 78n	0, 57n
7	93, 22n	-39, 40n	7, 02n	-0, 17n	56, 00n	-39, 43n	21, 8u	0, 18n	-45, 01n
8	39, 46n	-45, 40n	-39, 39n	55, 81n	0, 86n	55, 78n	0, 18n	21, 8u	0, 06n
9	6, 95n	39, 40n	93, 06n	39, 37n	54, 87n	0, 57n	-45, 01n	0, 06n	21, 8u

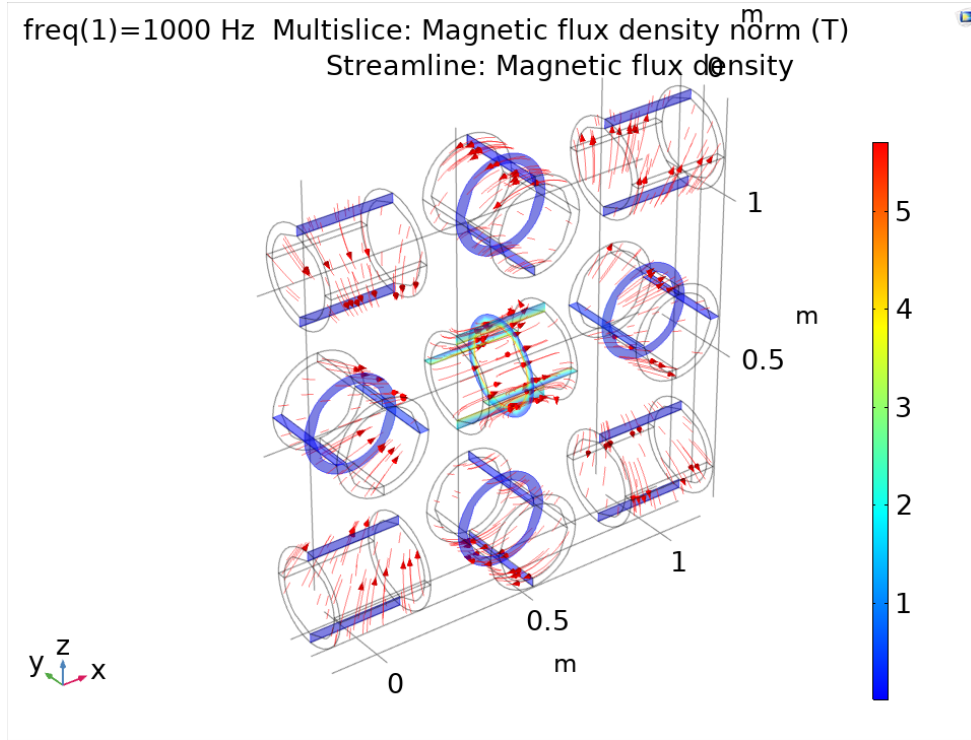


Figure 4.16: Magnetic flux density distribution of 3rd placement with 0.5m x 0.5m distances

Table 4.6: Inductance matrix of placement 3 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	0, 26n	94, 27n	0, 87n	55, 80n	-0, 19n	-45, 42n	-0, 03n	7, 08n
2	0, 26n	21, 8u	-0, 27n	-122, 4n	-0, 25n	-122, 4n	0, 02n	-45, 04n	0, 03n
3	94, 27n	-0, 27n	21, 8u	-0, 21n	55, 79n	0, 90n	7, 08n	-0, 02n	-45, 42n
4	0, 87n	-122, 4n	-0, 21n	21, 8u	-1, 57n	-45, 00n	1, 04n	-122, 4n	-0, 04n
5	55, 80n	-0, 25n	55, 79n	-1, 57n	21, 8u	-4, 66n	55, 80n	0, 24n	55, 79n
6	-0, 19n	-122, 4n	0, 90n	-45, 00n	-4, 66n	21, 8u	-0, 16n	-122, 3n	1, 06n
7	-45, 42n	0, 02n	7, 08n	1, 04n	55, 80n	-0, 16n	21, 8u	0, 28n	94, 27n
8	-0, 03n	-45, 04n	-0, 02n	-122, 4n	0, 24n	-122, 3n	0, 28n	21, 8u	-0, 22n
9	7, 08n	0, 03n	-45, 42n	-0, 04n	55, 79n	1, 06n	94, 27n	-0, 22n	21, 8u

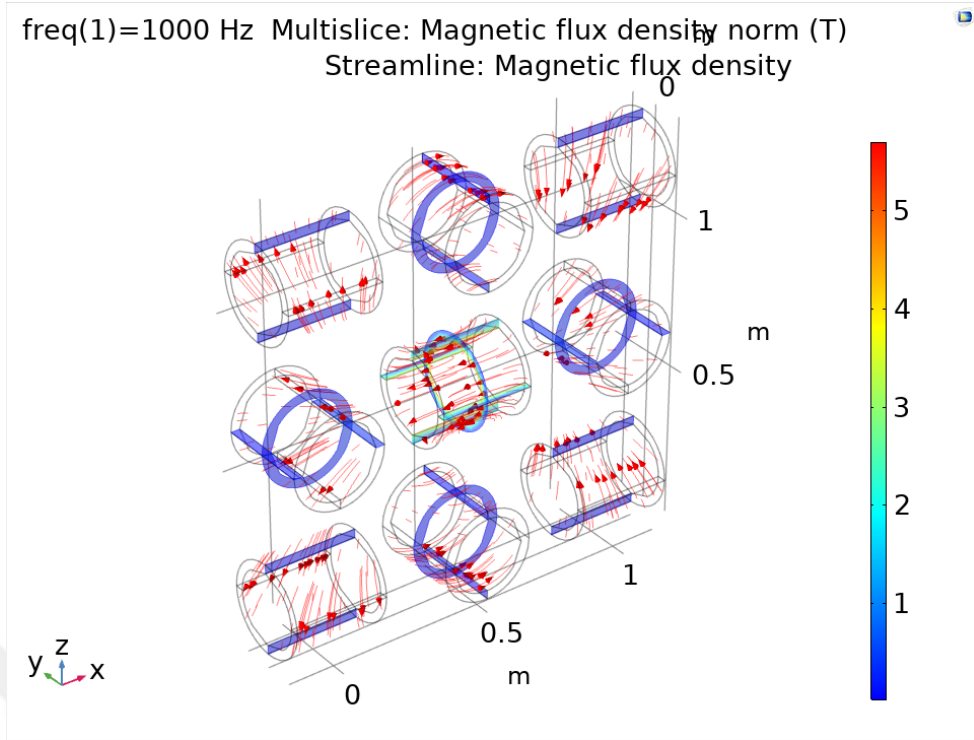


Figure 4.17: Magnetic flux density distribution of 4th placement with 0.5m x 0.5m distances

Table 4.7: Inductance matrix of placement 4 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	0, 25n	94, 26n	0, 86n	-55, 78n	0, 11n	-45, 42n	-0, 03n	7, 08n
2	0, 25n	21, 8u	-0, 27n	122, 3n	0, 23n	122, 3n	0, 02n	-45, 04n	0, 02n
3	94, 26n	-0, 27n	21, 8u	-0, 12n	-55, 82n	-0, 44n	7, 08n	-0, 02n	-45, 42n
4	0, 86n	122, 3n	-0, 12n	21, 8u	4, 34n	-44, 97n	0, 48n	122, 34n	-0, 16n
5	-55, 78n	0, 23n	-55, 82n	4, 34n	21, 8u	-1, 28n	-55, 76n	-0, 24n	-55, 85n
6	0, 11n	122, 3n	-0, 44n	-44, 97n	-1, 28n	21, 8u	-0, 01n	122, 3n	-0, 14n
7	-45, 42n	0, 02n	7, 08n	0, 48n	-55, 76n	-0, 01n	21, 8u	0, 30n	94, 27n
8	-0, 03n	-45, 04n	-0, 02n	122, 3n	-0, 24n	122, 3n	0, 30n	21, 8u	-0, 27n
9	7, 08n	0, 02n	-45, 42n	-0, 16n	-55, 85n	-0, 14n	94, 27n	-0, 27n	21, 8u

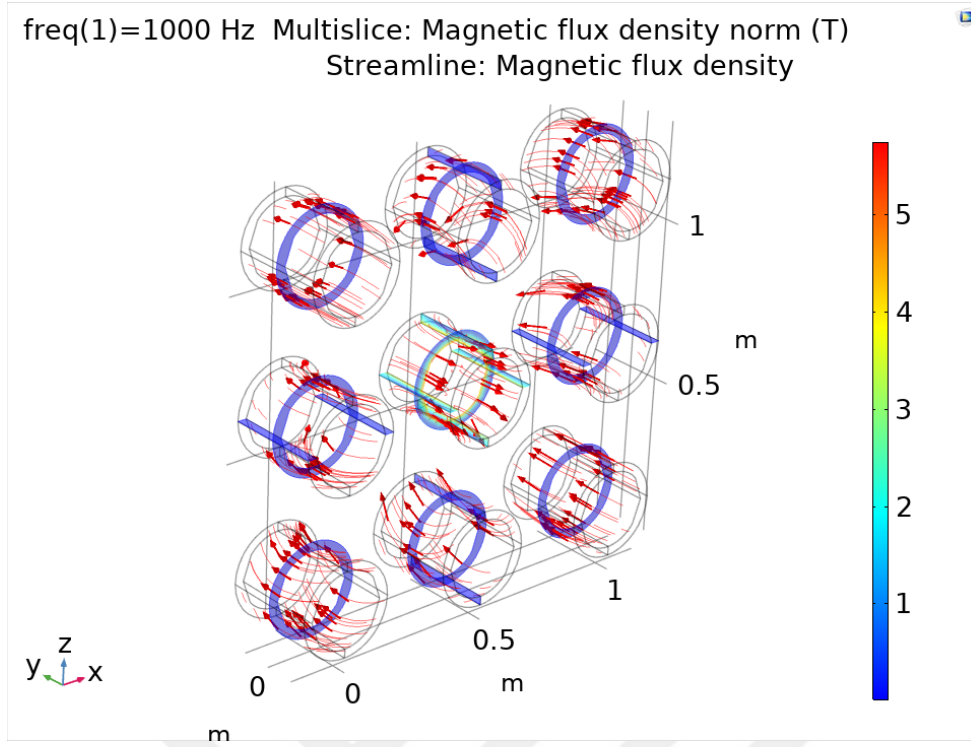


Figure 4.18: Magnetic flux density distribution of 5th placement with 0.5m x 0.5m distances

Table 4.8: Inductance matrix of placement 5 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	324n	-45, 02n	325, 3n	-122, 3n	32, 59n	-45, 06n	32, 63n	-16, 61n
2	324n	21, 8u	323, 8n	-122, 3n	325, 3n	-122, 3n	32, 63n	-45, 07n	32, 63n
3	-45, 02n	323, 8n	21, 8u	32, 61n	-122, 3n	325, 4n	-16, 62n	32, 64n	-45, 08n
4	325, 3n	-122, 3n	32, 61n	21, 8u	323, 7n	-44, 97n	325, 3n	-122, 4n	32, 60n
5	-122, 3n	325, 3n	-122, 3n	323, 7n	21, 8u	323, 9n	-122, 3n	325, 4n	-122, 3n
6	32, 59n	-122, 6n	325, 4n	-44, 97n	323, 9n	21, 8u	32, 59n	-122, 3n	325, 2n
7	-45, 06n	32, 63n	-16, 62n	325, 3n	-122, 3n	32, 59n	21, 8u	324, 1n	-45, 00n
8	32, 63n	-45, 07n	32, 64n	-122, 4n	325, 6n	-122, 3n	324, 1n	21, 8u	323, 9n
9	-16, 61n	32, 63n	-45, 08n	32, 60n	-122, 3n	325, 2n	-45, 00n	323, 9n	21, 8u

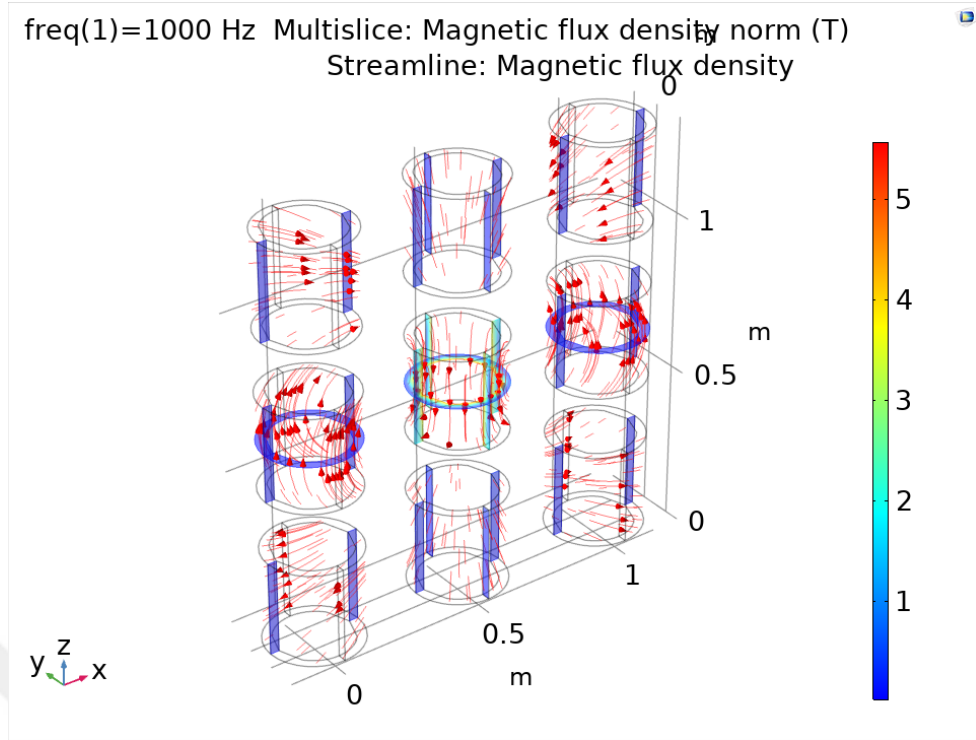


Figure 4.19: Magnetic flux density distribution of 6th placement with 0.5m x 0.5m distances

Table 4.9: Inductance matrix of placement 6 at 50cm horizontal and vertical distances from center to center in Henry (H)

	1	2	3	4	5	6	7	8	9
1	21, 8u	324n	-45, 02n	-809n	55, 79n	14, 29n	93, 11n	-45, 01n	7, 11n
2	324n	21, 8u	324n	56, 84n	-810n	54, 61n	-45, 10n	93, 20n	-45, 05n
3	-45, 02n	324n	21, 8u	14, 14n	55, 25n	-810n	6, 96n	-44, 95n	93, 17n
4	-809n	56, 84n	14, 14n	21, 8u	324n	-45, 01n	-810n	54, 90n	14, 21n
5	55, 79n	-810n	55, 25n	324n	21, 8u	324n	55, 80n	-809n	56, 63n
6	14, 29n	54, 61n	-810n	-45, 01n	324n	21, 8u	14, 11n	56, 27n	-810n
7	93, 11n	-45, 10n	6, 96n	-810n	55, 80n	14, 11n	21, 8u	324n	-45, 01n
8	-45n	93, 2n	-44, 95n	54, 90n	-809n	56, 27n	324n	21, 8u	324n
9	7, 11n	-45, 05n	93, 17n	14, 21n	56, 63n	-810n	-45, 01n	324n	21, 8u

4.1.6 Overall System Simulation with Mutual Inductance Matrices

After getting mutual inductance matrices, system-level simulations are run on the Simulink. As can be seen is the Simulink model shown in Figure 4.20, 9 modules are modeled and connected to the coupled inductors. Inside of each module block is also shown in Figure 4.21. The inductance matrix is imported to the coupled inductor. When any module is fired, the coupling effect could be observed on the other modules. Inductor currents, inductor voltages, and load currents of all modules are checked at every loop of the algorithm. Then, if current of a non-fired modules is higher than 0.001A, the case is called faulty, so that the distances are found to be not appropriate.

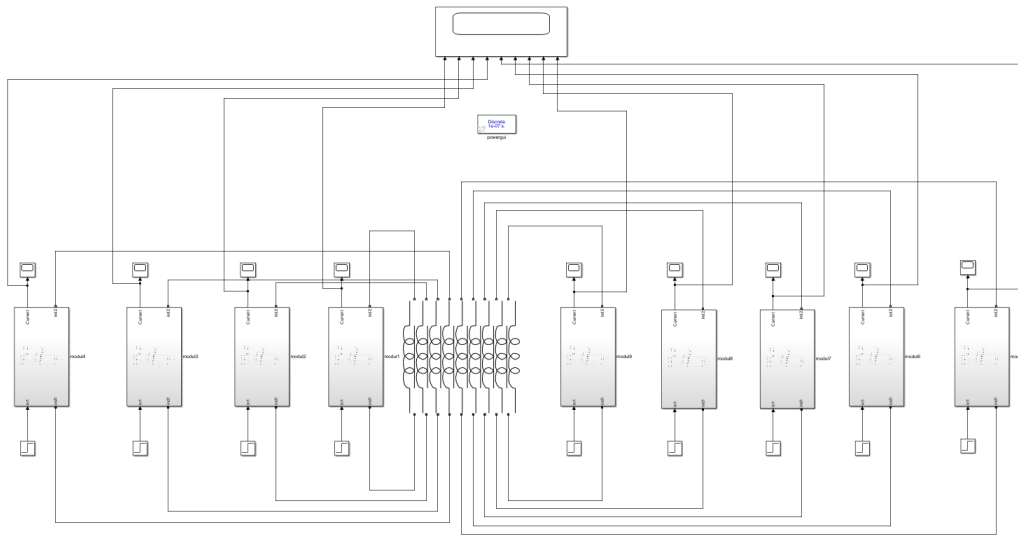


Figure 4.20: Overall Simulink model

The simulation results with the 1st inductor in Table 3.3 is given for three different horizontal and vertical distances combinations for placement 1 in Table 4.10. The optimum distances in this table are calculated with the proposed method. As can be seen, the optimum distances lay between the those of the non-faulty and faulty cases.

4.1.6.1 Simulation Results at Non-faulty Condition

If the modules are placed at safe distances with right orientations, diodes voltage does not exceed the opening voltage at the Worst of Bests switching cases. Figures 4.22 and 4.23 show the currents of modules. As Figure 4.23 shows that there is no current

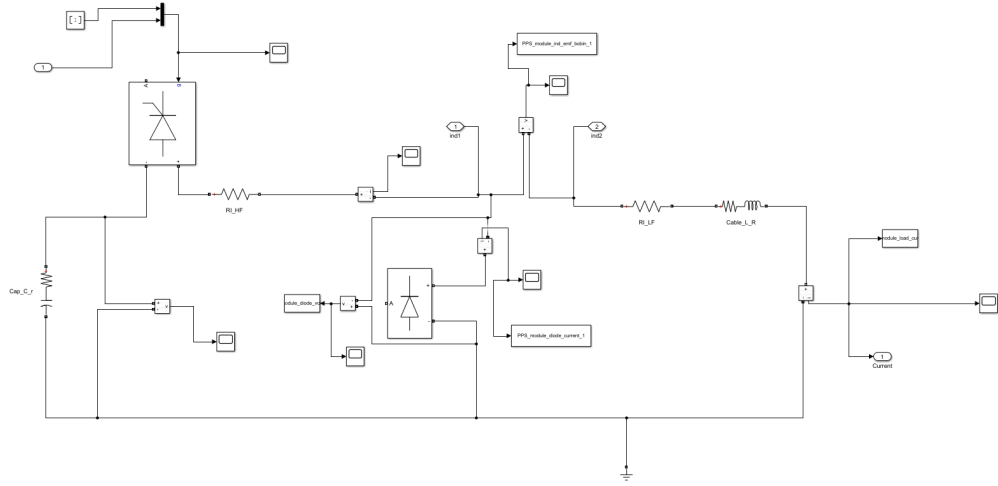


Figure 4.21: One module Simulink model

Table 4.10: Parameters of inductors used at section and distances for Placement 1 4.9a

Case	r_{inner}	Height	N_{turn}	Horizontal Dist.	Vertical Dist.
Non-faulty Case	0.12m	0.3m	12	0.9m	0.7m
Faulty Case	0.12m	0.3m	12	0.5m	0.5m
Optimum Distances	0.12m	0.3m	12	0,78m	0,56m

on the diodes, the current measured is 6.5mA. This condition is safe for the EML system.

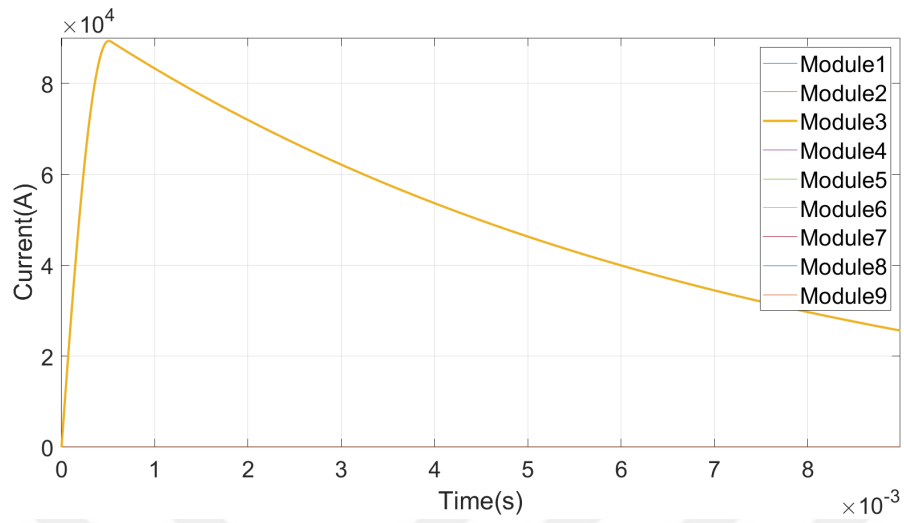


Figure 4.22: Load currents of all modules at non-faulty case

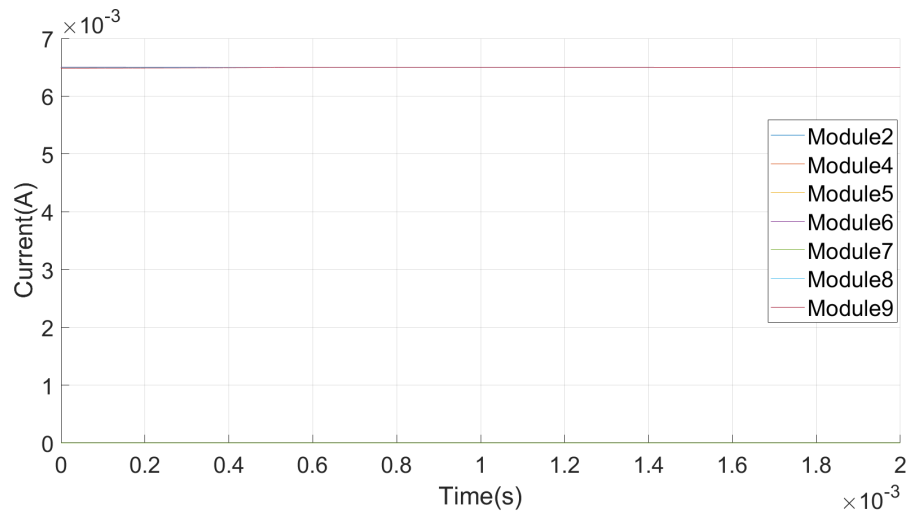


Figure 4.23: Load currents of non-fired modules at non-faulty case

4.1.6.2 Simulation Results at Faulty Condition

At the faulty condition, the Worst of Bests switching scenario of the placement and distances configurations is simulated and the non-fired modules currents are observed. Three diodes are connected in series in this model. So that if the voltage on the diodes exceeds 2.4V, diodes open. Figure 4.24 shows inductor voltage and current graphs of the fired module. This current induces some voltage on inductor and diodes are opened as can be seen in Figure 4.25. Figures 4.26 and 4.27 show the currents of the modules.

If any module fires after induced EMF opens the diode of this module, the diode side sees a high voltage and passes the current in the reverse way. This reverse current causes the break of the diode as mentioned before. As a result of Worst of Bests algorithm, only 9th module is fired at $t=0$ and also 1st, 2nd, 5th and 7th modules have faults. There are currents on the load although modules are not fired.

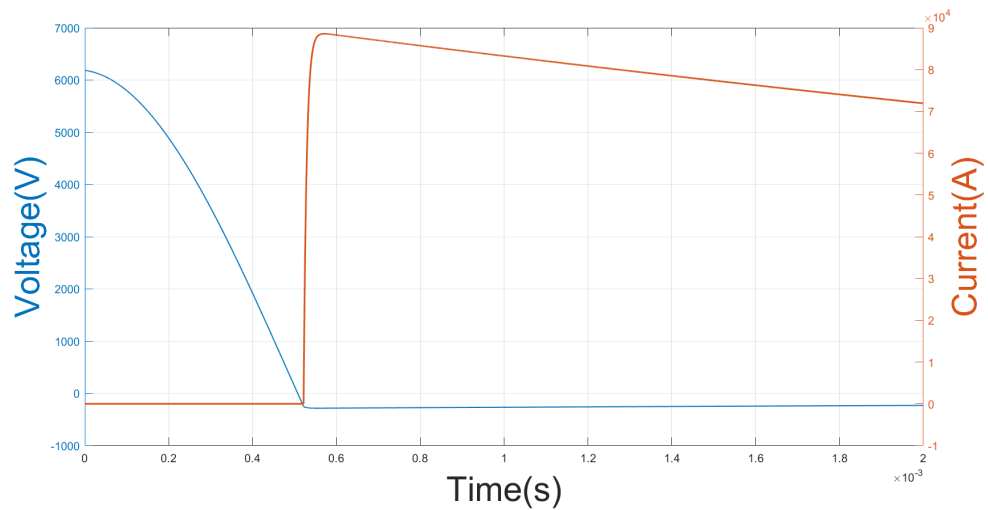


Figure 4.24: Voltage and current of fired module

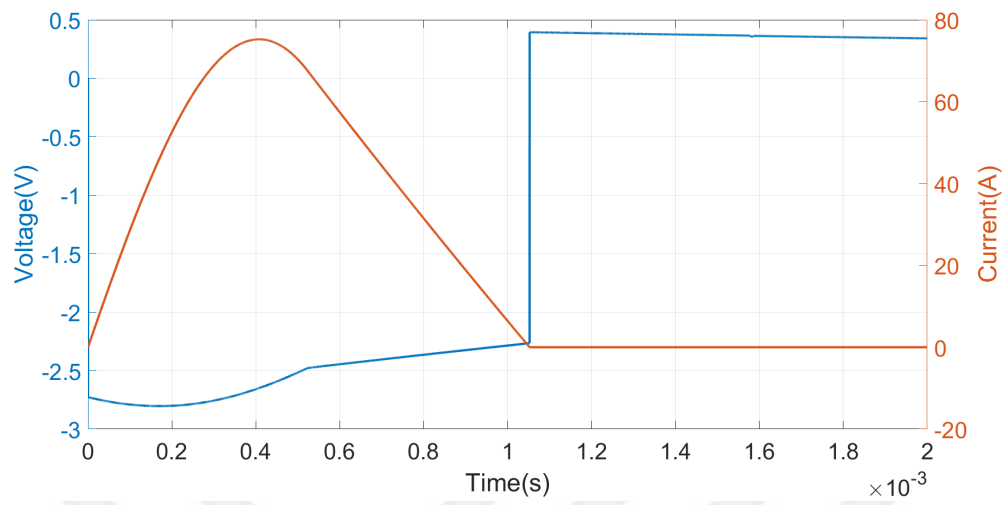


Figure 4.25: Voltage and current of a non-fired module that have fault

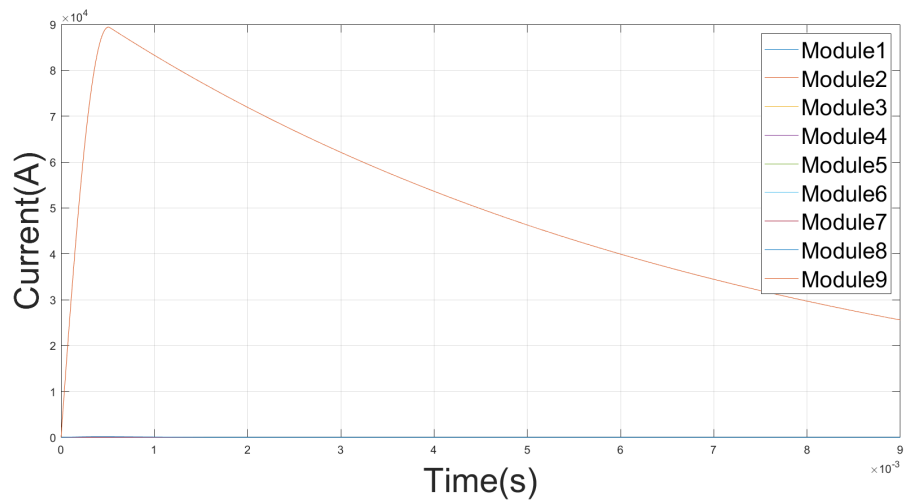


Figure 4.26: Load currents of all modules at faulty case

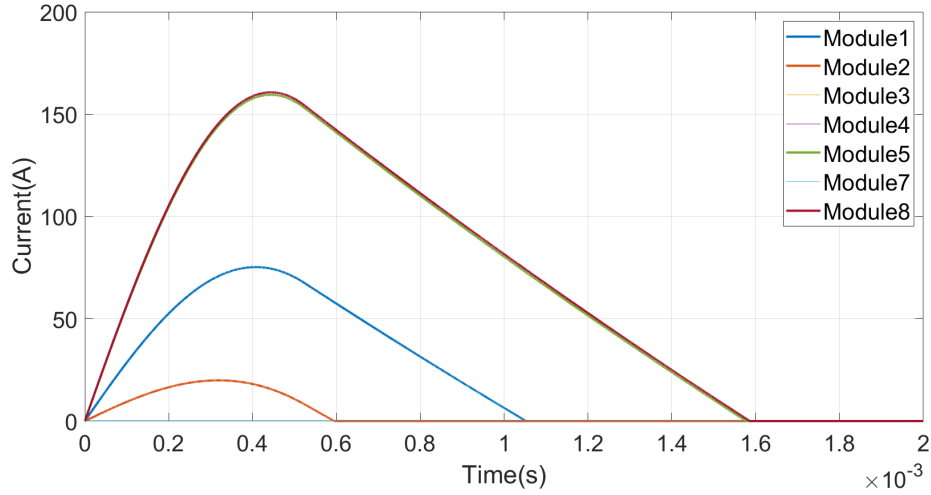


Figure 4.27: Load currents of non-fired modules at faulty case

4.1.7 Determination of Optimum Distances between Inductors

According to placement configurations and inductor types, optimum distances change. As mentioned in section 4.1.5, magnetic flux distributions affects the minimum safe distances. In other words, when distances increase, mutual effects decrease. In an other placement, it can be increased with increasing distances until some distances. The mapping section of the algorithm gives hints about changes in the induced EMF matrices. For example, 2nd placement configuration is the best one because induced voltage hardly exceeds the specified voltage level. Also, the value is better at the smaller distances and also at larger distances (Figure 4.29). In the 3rd placement, the optimum point is (0.38m, 0.38m) but, when distances increase, faults on the diodes can be seen as Figure 4.30 shows. Moreover, the 6th configuration is the worst one because EMF values are much higher than others (Figure 4.33).

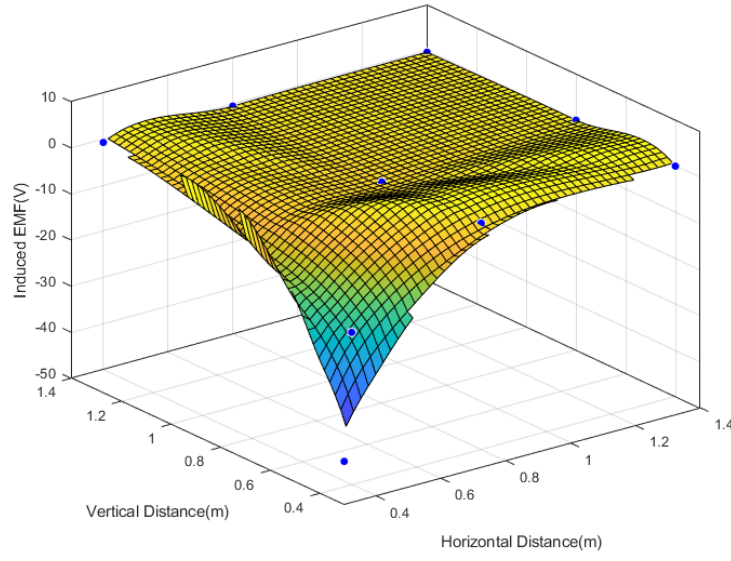


Figure 4.28: Mapping of EMF of the Worst of Bests switching case for the placement
1

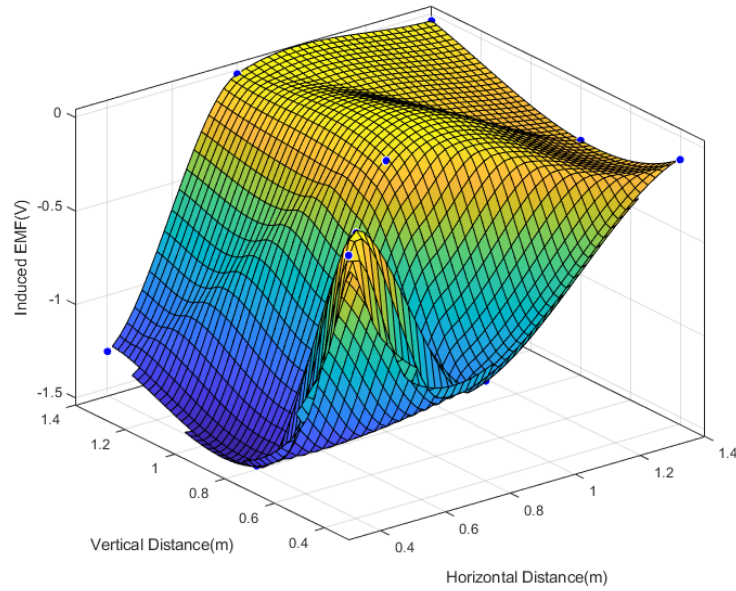


Figure 4.29: Mapping of the EMF of Worst of Bests switching case for the placement
2

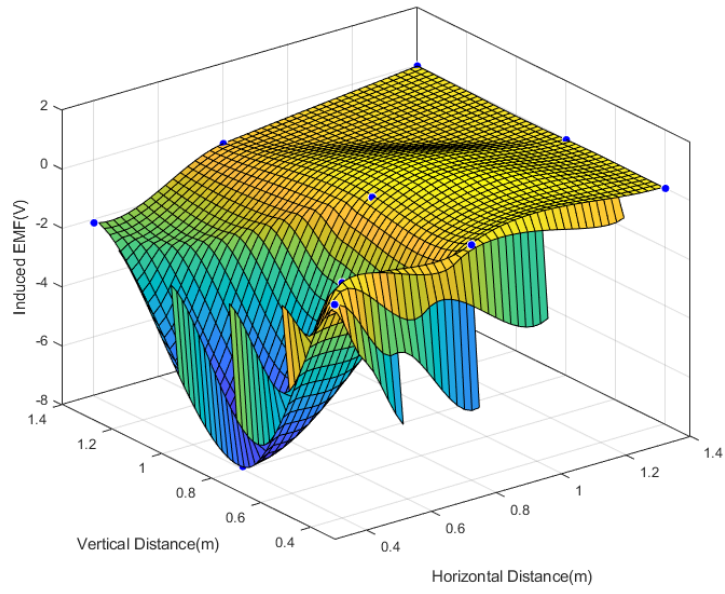


Figure 4.30: Mapping of the EMF of Worst of Bests switching case for the placement
3

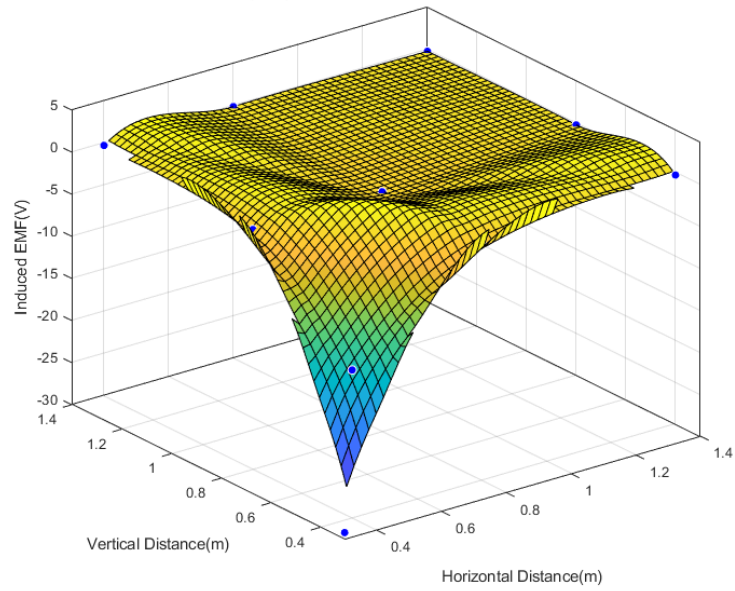


Figure 4.31: Mapping of the EMF of Worst of Bests switching case for the placement
4

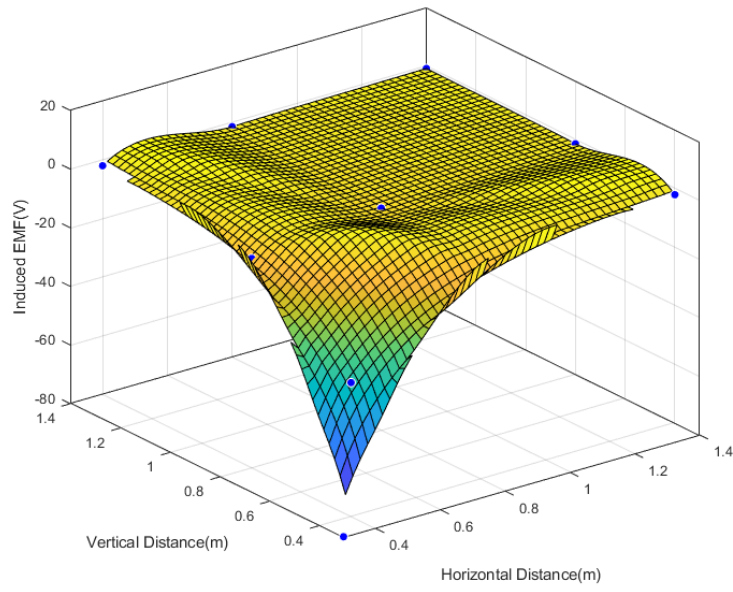


Figure 4.32: Mapping of the EMF of Worst of Bests switching case for the placement
5

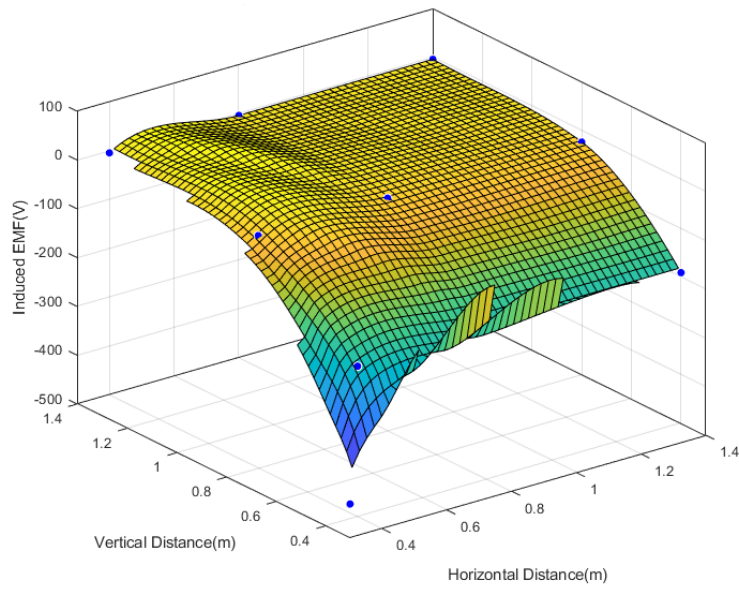


Figure 4.33: Mapping of the EMF of Worst of Bests switching case for the placement
6

4.1.8 Results of the Algorithm

Table 4.11 shows the results of the overall algorithm. According to the needs, inductor type and placement configuration could be chosen, and the design process of the power unit of any EML system could start from here. The results suggest that a compact system can be designed if inductor 5 from Table 3.3 and placement 2 or 3 are chosen. The minimum safe horizontal and vertical distances are found to be 0,31m each under both placements. Based on the other comparisons, placement 2 can be prioritized due to its more steady EMF. The results presented here show the need for applying the algorithm to various inductors and placements.

By the way, this algorithm was developed generically. In other words, variables such as coil type, energy level, maximum current limit, placement configurations can be easily changed, the algorithm can be run, and placement analysis can be performed.

Placement analysis gives us optimal distances but there can be always a worst-case switching scenario to cause faults on one of the diode. So, the switching scenarios should be chosen carefully. In Chapter 5, a generated method for determining the switching sequence is examined.

Table 4.11: Optimum distances for placements of first 5 inductors at Table 3.3

Inductor	Placement	$h_{ind}(m)$	$r_{in}(m)$	N_{turn}	$D_{horz}(m)$	$D_{vert}(m)$
1	1	0, 3	0, 12	12	0, 78	0, 56
1	2	0, 3	0, 12	12	0, 37	0, 37
1	3	0, 3	0, 12	12	0, 40	0, 40
1	4	0, 3	0, 12	12	0, 90	0, 92
1	5	0, 3	0, 12	12	1, 28	1, 28
1	6	0, 3	0, 12	12	1, 46	2, 19
2	1	0, 26	0, 12	11	0, 92	0, 93
2	2	0, 26	0, 12	11	0, 38	0, 38
2	3	0, 26	0, 12	11	0, 42	0, 42
2	4	0, 26	0, 12	11	0, 78	0, 85
2	5	0, 26	0, 12	11	1, 21	1, 21
2	6	0, 26	0, 12	11	1, 39	2, 14
3	1	0, 24	0, 12	11	1, 02	0, 87
3	2	0, 24	0, 12	11	0, 38	0, 38
3	3	0, 24	0, 12	11	0, 40	0, 40
3	4	0, 24	0, 12	11	0, 84	0, 84
3	5	0, 24	0, 12	11	1, 21	1, 21
3	6	0, 24	0, 12	11	1, 30	2, 10
4	1	0, 26	0, 11	12	0, 62	1, 30
4	2	0, 26	0, 11	12	0, 35	0, 35
4	3	0, 26	0, 11	12	0, 39	0, 39
4	4	0, 26	0, 11	12	0, 83	0, 43
4	5	0, 26	0, 11	12	1, 15	1, 15
4	6	0, 26	0, 11	12	1, 33	2, 02
5	1	0, 28	0, 1	13	0, 51	1, 09
5	2	0, 28	0, 1	13	0, 31	0, 31
5	3	0, 28	0, 1	13	0, 31	0, 31
5	4	0, 28	0, 1	13	0, 32	0, 65
5	5	0, 28	0, 1	13	1, 09	1, 09
5	6	0, 28	0, 1	13	1, 30	1, 97

4.1.9 Verification of the One Module Model

Verification of the overall system was not possible. Instead, Simulink model of the one module is verified with the experiment. The module is charged to 6500V and discharged on 2 parallel cables so a short circuit test is applied. Tests with rails and armature were also not possible. The module has 2 parallel capacitor blocks and 2 parallel pulser blocks as seen in Figure 4.34. The diode packs and thyristor packs have 3 serial diodes and thyristors. Capacitor and pulser parameters are taken from the producer reports. Inductor parameters are calculated with COMSOL 2D with the used method in previous parts. Also, other important parameters are parameters of the discharge cables. These values are measured with an LCR meter, results are shown in Figure 4.35. Parameters of the test module are shown in Table 4.12. Measured and simulated capacitor voltage, load current and thyristor current values are compared in Figures 4.37, 4.38 and 4.39, respectively. Current and voltage waveforms of the Simulink model are well-matched with experimental results. This means currents, the slope of currents and as a result induced EMF values of each module could be simulated by the Simulink model.

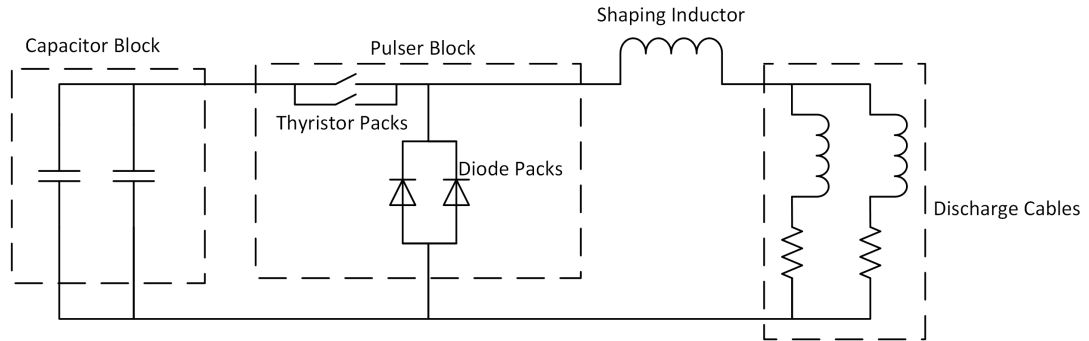
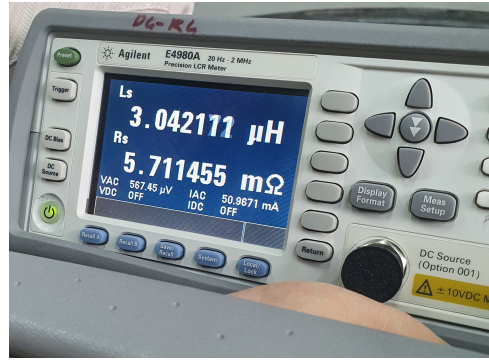


Figure 4.34: Pulse power supply that used at experiment



(a) Cable 1



(b) Cable 2

Figure 4.35: Impedance values of discharge cables at 500Hz

Table 4.12: Parameters of the test module

L_{Cable1}	Inductance value of the discharge Cable 1	$3.17\mu H$
L_{Cable2}	Inductance value of the discharge Cable 2	$3.04\mu H$
R_{Cable1}	Resistance value of the discharge Cable 1	$5.7m\Omega$
R_{Cable2}	Resistance value of the discharge Cable 2	$5.7m\Omega$
L_{Cap}	Inductance value of the capacitors	$0.3\mu H$
R_{Cap}	Resistance value of the capacitors	$0.5m\Omega$
C_{Cap}	Capacitance value of the capacitors	$5.9mF$
R_{Thy}	Resistance value of one branch thyristor packs	$0.675m\Omega$
L_{Diode}	Inductance value of one branch diode packs	$0.3\mu H$
R_{Diode}	Resistance value of one branch diode packs	$0.3m\Omega$
L_{Ind}	Inductance value of the pulse shaping inductance	$20\mu H$
R_{Ind-LF}	Resistance value of the pulse shaping inductance for 500Hz	$0.405m\Omega$
R_{Ind-HF}	Resistance value of the pulse shaping inductance for 1kHz	$0.406m\Omega$
f_0	Resonant frequency	$10.3Hz$

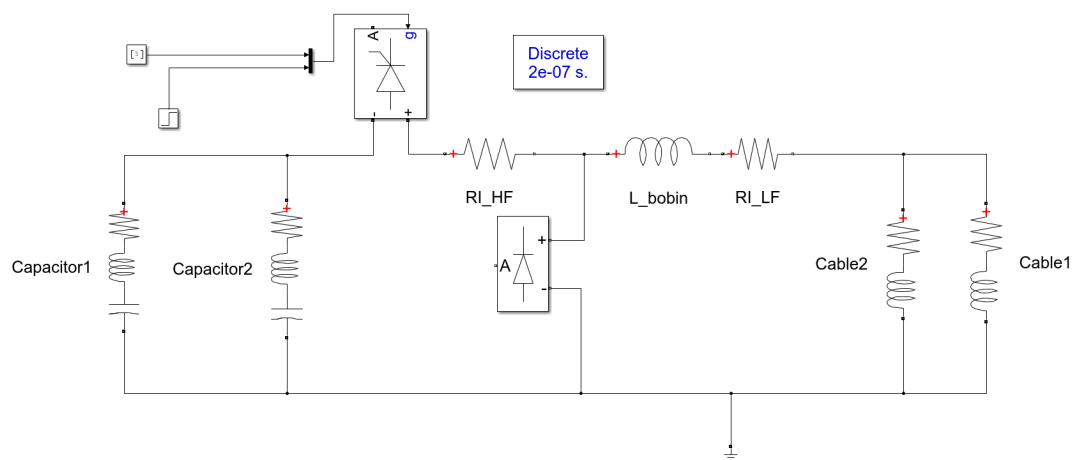


Figure 4.36: Simulink setup for one module verification

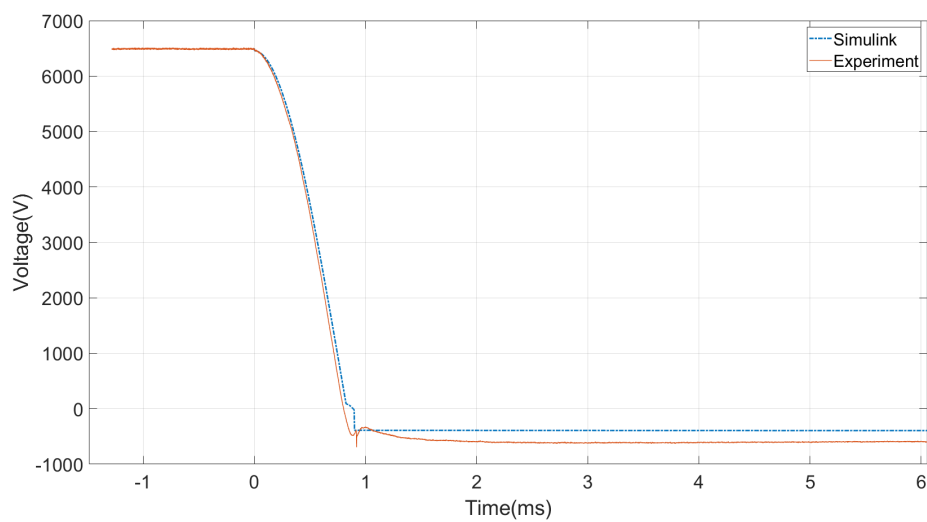


Figure 4.37: Capacitor voltages of the 1 module firing

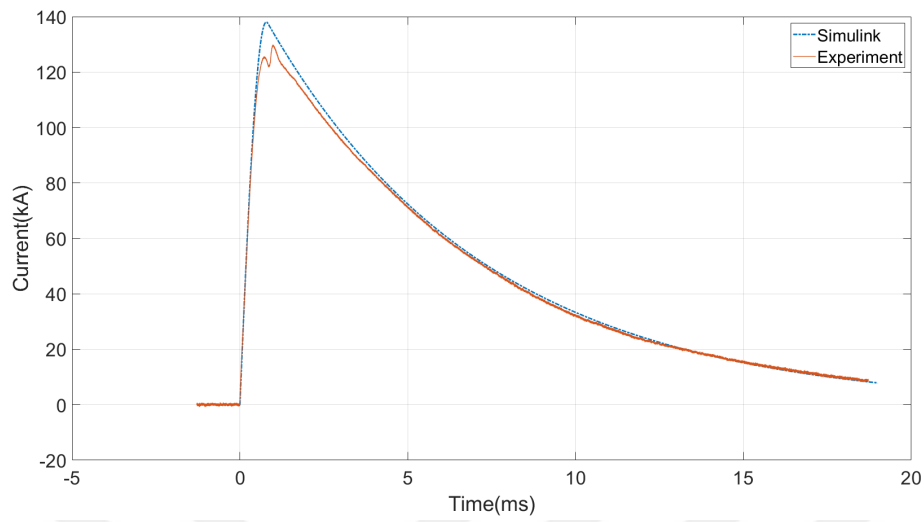


Figure 4.38: Load currents of the 1 module firing

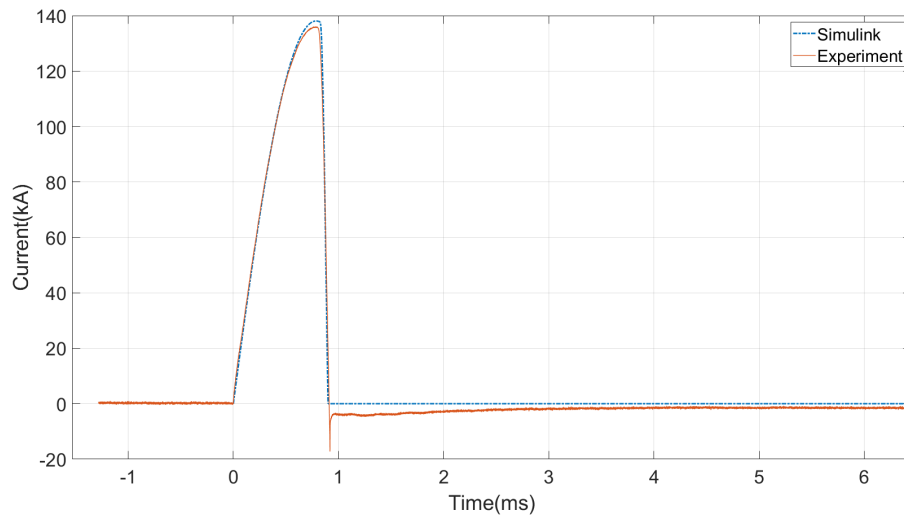


Figure 4.39: Thyristor currents of the 1 module firing

CHAPTER 5

OPTIMUM SWITCHING ALGORITHM

The algorithm which explained in previous parts is used to find the optimum distances between modules for selected inductance and placement by using Worst of Bests switching states. But there is a state which causes fault on some modules for each firing combination at any firing step in general. It means each firing state could open some of diodes of non-fired modules. To prevent this situation, Optimum Switching Algorithm (OSA) is developed. It matches the firing sequence and the fired modules. It uses inductance matrix, $\frac{di}{dt}$ and firing combinations. For example, there are 9 switching combinations for 1 module firing $\binom{9}{1}$, 36 combinations for 2 modules switching $\binom{9}{2}$, 84 combinations for 3 modules switching $\binom{9}{3}$ and so on. Induced EMF on non-fired modules are calculated for all combinations. If more than 1 modules are fired, sum of induced EMFs induced by the fired modules on any non-fired module is calculated. By this way, total voltage on the diodes are found. Finally, EMF matrices shows us if the firing action causes a diode fault or not.

Combinations of the any number of firings are sorted based on the mean EMF value of non-fired modules. Then, the algorithm starts from top of the 1st step number of firing combination matrices. It takes a row (firing state) which has maximum positive mean value. The negative induced value opens diodes if it is smaller than $-2.4V$ as mentioned previously. At the 2nd step, modules that will fire are chosen based on the first steps induced EMF row according. Algorithm chooses modules that have higher induced EMF value which will not open the diode on any module. And at other steps, same algorithm called again. Figure 5.1 and 5.2 show the steps of the algorithm.

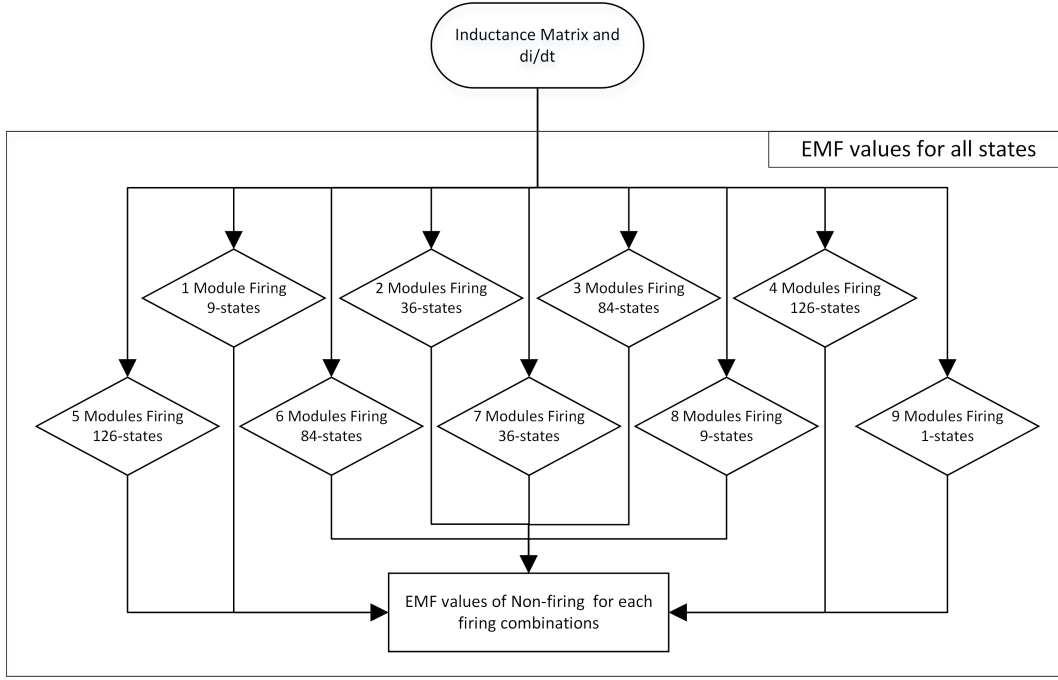


Figure 5.1: Outline of EMF calculations of the all firing combinations

5.1 Examples of Optimum Switching Algorithm

Examples are generated with the following inductance matrix given in Table 5.1 and $\frac{di}{dt}$ value is chosen 2×10^8 . To show the operation of the algorithm, firing steps are chosen randomly. The results for a firing sequence of firing sequence of 3+2+2+1+1 are shown in Table 5.2, the algorithm decides to fire modules 1, 3 and 8 in the first step; modules 2 and 9 in the second step; modules 5 and 6 in the third step; module 4 in the forth step and module 7 in the last step. As can be seen from the induced voltages of the modules fired in the previous step, there are no faulty situations. In Tables 5.2, 5.3, 5.4 and 5.5, there is no dangerous induced EMF on the previous steps of the fired modules also so when any module is fired in the desired sequence, the probability of diode failure is significantly reduced. Safe operation can be achieved with this method.

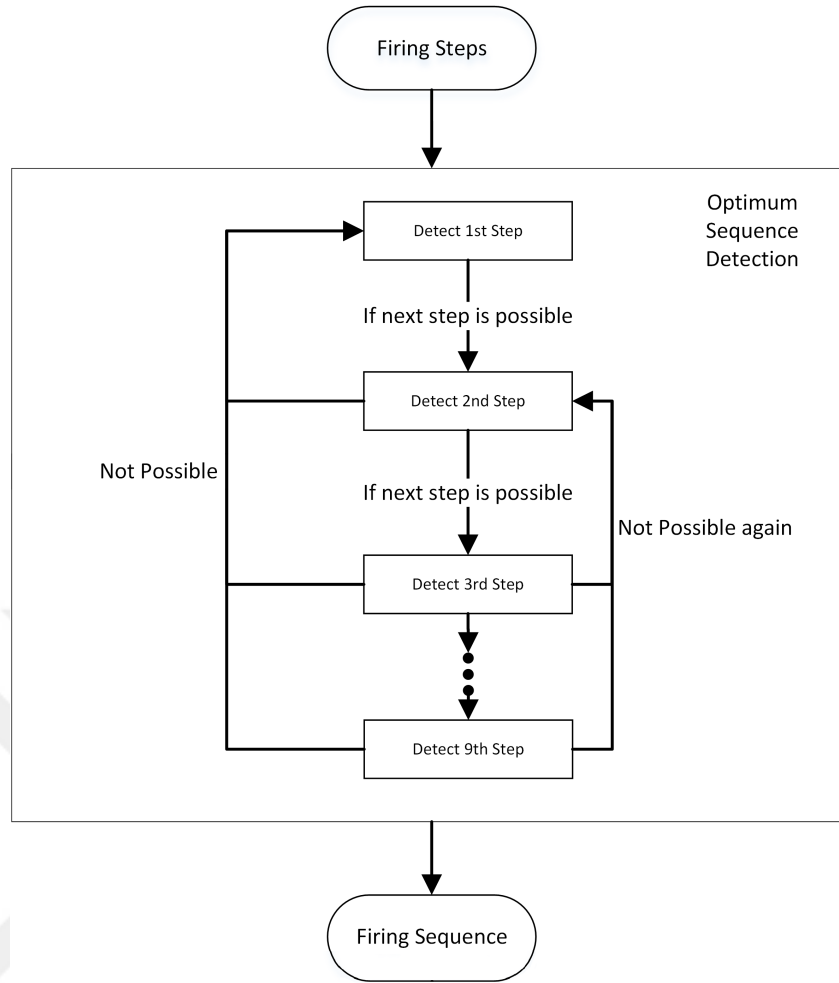


Figure 5.2: Outline of the selection of the modules for each firing step

5.2 Discussion of the results of the OSA

It was stated that the diodes were opened at -2.4 volts. In the Tables 5.2, 5.3, 5.4 and 5.5, the induced voltages caused by the coil of the fired module are seen in each row. These voltages are dangerous for coils that are not yet fired if the diode is opened during firing. The diodes of modules with a negative voltage greater than 2 volt induced in the coil and therefore be dangerous to fire and should not be fired in the next step. As seen in the examples, any inductor of modules that have a negative voltage greater than 1 volt was not fired in the next step but was fired in the other steps. This method has also increased the security of the system.

Table 5.1: Inductance matrix (H) of examples

$21.3u$	$39, 9n$	$-5, 09n$	$39, 6n$	$-14, 0n$	$3, 67n$	$-5, 02n$	$3, 65n$	$-1, 87n$
$39, 9n$	$21.3u$	$39, 9n$	$-14, 0n$	$39, 5n$	$-14, 0n$	$3, 64n$	$-5, 02n$	$3, 64n$
$-5, 09n$	$39, 9n$	$21.3u$	$3, 68n$	$-14, 0n$	$39, 6n$	$-1, 87n$	$3, 65n$	$-5, 03n$
$39, 6n$	$-14, 0n$	$3, 68n$	$21.3u$	$40, 0n$	$-5, 09n$	$39, 5n$	$-14, 0n$	$3, 67n$
$-14, 0n$	$39, 5n$	$-14, 0n$	$40, 0n$	$21.3u$	$40, 0n$	$-14, 0n$	$39, 6n$	$-14, 0n$
$3, 67n$	$-14, 0n$	$39, 6n$	$-5, 09n$	$40, 0n$	$21.3u$	$3, 67n$	$-14, 0n$	$39, 5n$
$-5, 02n$	$3, 64n$	$-1, 87n$	$39, 5n$	$-14, 0n$	$3, 67n$	$21.3u$	$40, 0n$	$-5, 09n$
$3, 65n$	$-5, 02n$	$3, 65n$	$-14, 0n$	$39, 6n$	$-14, 0n$	$40, 0n$	$21.3u$	$40, 0n$
$-1, 87n$	$3, 64n$	$-5, 03n$	$3, 67n$	$-14, 0n$	$39, 5n$	$-5, 09n$	$40, 0n$	$21.3u$

Table 5.2: Firing sequence and diode voltages of non-fired modules, Steps: 3+2+2+1+1

.	M1	M2	M3	M4	M5	M6	M7	M8	M9
Step1	Fire	14, 99	Fire	5, 85	2, 30	5, 84	6, 62	Fire	6, 64
Step2	-	Fire	-	-2, 08	5, 09	5, 11	-0, 29	-	Fire
Step3	-	-	-	7, 00	Fire	Fire	-2, 08	-	-
Step4	-	-	-	Fire	-	-	7, 92	-	-
Step5	-	-	-	-	-	-	Fire	-	-
Step6	-	-	-	-	-	-	-	-	-
Step7	-	-	-	-	-	-	-	-	-
Step8	-	-	-	-	-	-	-	-	-
Step9	-	-	-	-	-	-	-	-	-

Table 5.3: Firing sequence and diode voltages of non-fired modules, Steps: 1+1+1+1+1+1+1+1+1

.	M1	M2	M3	M4	M5	M6	M7	M8	M9
Step1	7,99	Fire	8,00	-2,81	7,90	-2,81	0,73	-1,01	0,73
Step2	-1,01	-	-0,38	7,92	-2,81	0,74	Fire	8,00	-1,02
Step3	-1,02	-	Fire	0,74	-2,81	7,92	-	0,73	-1,01
Step4	7,93	-	-	Fire	8,02	-1,02	-	-2,82	0,74
Step5	Fire	-	-	-	-2,81	0,74	-	0,73	-0,38
Step6	-	-	-	-	-2,81	7,92	-	8,02	Fire
Step7	-	-	-	-	8,01	Fire	-	-2,82	-
Step8	-	-	-	-	Fire	-	-	7,92	-
Step9	-	-	-	-	-	-	-	Fire	-

Table 5.4: Firing sequence and diode voltages of non-fired modules, Steps: 2+5+1+1

.	M1	M2	M3	M4	M5	M6	M7	M8	M9
Step1	6,97	Fire	Fire	-2,08	5,09	5,11	0,35	-0,28	-0,28
Step2	Fire	-	-	20,02	Fire	Fire	Fire	Fire	11,73
Step3	-	-	-	0,74	-	-	-	-	Fire
Step4	-	-	-	Fire	-	-	-	-	-
Step5	-	-	-	-	-	-	-	-	-
Step6	-	-	-	-	-	-	-	-	-
Step7	-	-	-	-	-	-	-	-	-
Step8	-	-	-	-	-	-	-	-	-
Step9	-	-	-	-	-	-	-	-	-

Table 5.5: Firing sequence and diode voltages of non-fired modules, Steps: 4+1+1+3

.	M1	M2	M3	M4	M5	M6	M7	M8	M9
Step1	15, 63	Fire	Fire	Fire	21, 03	1, 28	16, 27	Fire	8, 48
Step2	-1, 01	-	-	-	-2, 81	0, 74	Fire	-	-1, 02
Step3	0, 74	-	-	-	8, 01	Fire	-	-	7, 92
Step4	Fire	-	-	-	Fire	-	-	-	Fire
Step5	-	-	-	-	-	-	-	-	-
Step6	-	-	-	-	-	-	-	-	-
Step7	-	-	-	-	-	-	-	-	-
Step8	-	-	-	-	-	-	-	-	-
Step9	-	-	-	-	-	-	-	-	-

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

In this thesis, firstly, the necessary inductance value of the shaping inductor is calculated according to the conservation of the energy formula. In this way, the maximum current value is limited by the shaping inductor. This enables the protection of the semiconductors of the modules. After the minimum inductance value is decided, the design of the inductor starts. In the inductor design, there are three main design parameters, they are inner radius, length, and the number of turns. Inductance value increase with an increasing number of turn and inner radius. And also, the pressure on the inductor increases with decreasing inner radius and length. Optimum inductor designs are chosen with an error function based on pressure, inductance, and resistance values. In this wise, the required inductance value is obtained with minimum pressure and resistance values. Optimum placement based on orientation and spacing distances between inductors is made by a developed algorithm. Some orientations are desired and distances are searched by starting from initial distances which are found by mapping method.

According to the output of the overall algorithm, when the inner radius increase, the induced emf of the inductor increases. There is a trade-off here, when the inner radius decreases, lateral pressure of the inductor increases but modules distances should increase. The algorithm sees that the Worst of Best switching combination results to arrange distances. Best combinations should be chosen to work the system safer. Modules could be switched either simultaneously or separately. If modules are fired separately, modules to be fired at each step should be selected carefully. The optimum switching algorithm proposed in this study find the best modules to fire in the desired

time sequences to prevent fault.

The developed and proposed design, methods and algorithms can be used to obtain a compact and safe PPS.

The outputs and findings of the thesis can be summarized as follows:

- Inductance calculation of the shaping inductors are made more accurately by using FEA simulation.
- Pressure estimation of the inductors is made by FEA and this enables us to take precautions against mechanical failure of inductors.
- A method for selection of a proper shaping inductor is proposed, which can be adapted any energy, voltage level, any semiconductor types, any material types, etc.
- This study shows the importance of the orientation of the shaping inductors on the modules. And also it shows that the basic orientations in which all modules have the same orientation are not usable in real life applications.
- One of the most important contributions of this study to the literature is the proposed methodology that is developed for the determination of inductor placement.
- It is found that the higher separation distances between inductors are not always good, because at the some orientations, system is found to be safer at the closer inductors placement. Magnetic flux distribution affects it.
- Each orientation type has different spacing between inductors for each inductor design.
- Even if inductors are placed safely, the worst firing scenarios could cause some faults. Therefore, an optimum switching algorithm is needed to select a safer scenario. A method to obtain an optimized switching algorithm is proposed in this study.

Finally, if the design is made according to the thesis outputs, the system will work safer.

6.2 Future Work

This thesis gives important pieces of information on the design process of the shaping inductors of pulse power supplies and this study can be enhanced by the following future work.

First of all system-level verification could not be made because the test system was not available. Verification of the overall system can be suggested as a future work. As some of the modules are fired, induced voltage on the inductor at any non-fired module can be measured. It is not expected to obtain the same results as the simulation because there are a lot of metal components in the container near the inductors. Secondly, magnetic shielding can be used to decrease mutual inductance values between the inductors. Some simulation is made with magnetic shields but results are immature to share. It is expected that the spacing between inductors decreases a little bit with shielding. Shielding performance can be improved by changing the thickness and material of the shield.

Thirdly, different types of inductors like toroid inductors can be included in the algorithm. At a high energy level, it is expected that the leakage will be higher on the toroid inductors but the spacing between inductors can be decreased when such an inductor is used, and also orientation problems can be solved.



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