Analysis and Simulation of EM Fields of a Permanent Magnets DC Linear Motor used to Propel a Magnetically Levitated Train

By

Orlando Leal Flórez

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2004

Approved by:

[redacted] 20 May 2004

Rafael A. Rodríguez Solís, Ph.D. — Date
Member, Graduate Committee

[redacted] May 20, 2004

David Serrano, Sc.D. — Date
Member, Graduate Committee

[redacted] May 20 2004

Agustín A. Irizarry-Rivera, Ph.D. — Date
Chairperson, Graduate Committee

[redacted] May 20 2004

Paul Castillo, Ph.D. — Date
Representative of Graduate Studies

[redacted] May 20, 2004

Jorge Ortiz Álvarez, Ph.D. — Date
Chairperson of the department

ABSTRACT

The Berdut design is a new alternative with permanent magnets for Maglev transport. The magnetic field and the force generated by the Berdut design were explored for the first time by mean of simulations using the software program Maxwell 2D Version 9. Using mainly the force and magnetic field as the analysis method the importance, effect and function of each element were studied to determine the pros and cons of this alternative. As result some materials were recommended in order to optimize the force magnitude. The main source for dimensions and materials were the patents of this design and Mr. Berdut.

RESUMEN

El diseño de Berdut es una nueva alternativa para el transporte masivo basado en levitación magnética con imanes permanentes. El campo magnético y la fuerza generados por el diseño de Berdut fueron por primera vez explorados usando simulaciones realizadas en Maxwell 2D versión 9. Usando principalmente la fuerza y el campo magnético como método de análisis la importancia, el efecto y función de cada componente fueron estudiados para determinar las ventajas y las desventajas de esta alternativa. Como resultado algunos materiales fueron recomendados com el objetivo de optimizar la fuerza. La principal fuente de información para las dimensiones y los materiales fueron las patentes del diseño de Berdut y el propio señor Berdut.

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DEDICATION

To my family specially my father Orlando and my mother Maria Teresa for all their sacrifices and their unconditional support in all my life. To my brother Ervin and my sister Jenny without them my life would be bored. To Leticia for all her patience, support and love.

ACKNOWLEDGMENTS

I would like to thank Dr. Agustin Irizarry. His fundamental guidance and support during the production of this research are greatly appreciated.

Finally, I have to thank all the professors of University of Antioquia and University of Puerto Rico that during my academic life taught me very important things of life and engineering.

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Chapter 1

Introduction

Massive transport has had a big role in society, passengers as well as cargo have been its inspiration. Cost and low capacity seriously impair air transport of cargo and the ship alternative has big geographical limitations. Trains have emerged as a solution. Conventional trains responded to the challenge for a long time but the continuous and prolonged increase of passengers and cargo demanded faster and more efficient trains. Bullet trains were created and, for a while they did their best and maybe nowadays they continue as an alternative. Bullet trains have reached more velocity than normal trains but due to the friction their velocity has been limited to 300 Km/hr [1].This limitation trends to reduce train leadership in the massive transport race.

Japan and Germany pioneered the development of magnetic levitation (maglev) in the transport chapter and so far this is a promising and prosperous alternative because of levitation eliminates the friction as a velocity limiting factor leaving just the drag. As a result 500 Km/hr can be reached with additional "accessories" like safety, efficiency and comfort. Low noise, environmental friendliness and pollution free represent big credits for this technology [1, 2]. Japan, since 1970, is working on maglev trains and at present its work has been tested at the industrial scale [1]. In addition to Germany and Japan, other countries work in maglev transport but the researching has no been conclusive such as in the United States.

The Japan and Germany alternatives present high costs inherent to the superconductors, the complex control systems and the necessity of powering in order to reach levitation. To overcome these problems new alternatives have been proposed like Inductrack and Berdut design. The Lawrence Livermore National

Laboratory is working on the Inductrack. This alternative is totally different to their Japan and Germany pairs [3]. At present the Inductrack is in the initial phase and industrial tests have not been run. Differences in costs, construction and levitation mechanism are the important factors for the Inductrack. A similar alternative have been proposed by Mr Berdut in some patents. This alternative consists of a geometric configuration based on permanent magnets interlaced with Tee's of cast Iron or another ferromagnetic material [5-8]. This alternative concentrates the magnetic field in the Tee's and by interaction between the concentrated magnetic field and the magnetic field generated by several windings as they pass through the mentioned configuration, propulsion of the vehicle is reached. Figure 1.1 shows the 2D view and 3D view of the Berdut geometry.

Switzerland presents a new Maglev alternative for massive transport and this consists of a train working under a partial vacuum of less than 10 KPa. The vehicles will run in tunnels of 5 m of diameter under the partial vacuum reducing the aerodynamic drag forces [4] however this research remains unpublicized and hardly any internet information can be found.

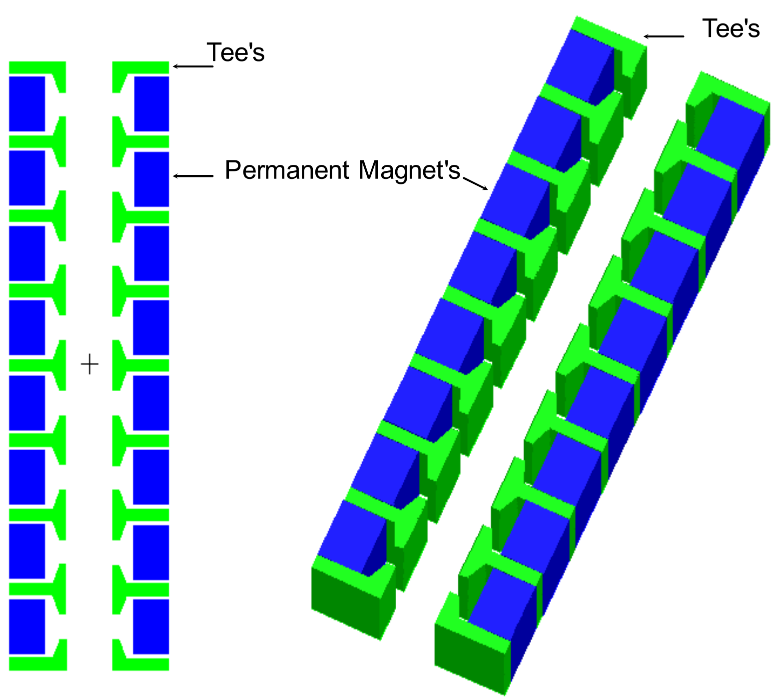


Figure 1.1. Berdut Geometry. 2D and 3D View.

A review of the different Maglev propulsion alternatives will be developed and this will facilitate the comparison among them in order to identify advantages and disadvantages of each one. Finally the magnetic characteristics of the Berdut train, the research object of this thesis, will be presented and this will help to elucidate the differences and advantages corresponding to this alternative. Also the importance, function and effect of each Berdut design component will be analyzed as a function of generated force and the magnetic filed for the first time. This analysis will take place thought a set of finite element simulations. The objectives of our work are:

— Perform for first time an analysis of the magnetic field and force generated in the Berdut design

— Analyze the function and effect of each component in the magnetic field and force.

— Based on the force analysis to determine an adequate commutation point.

— Analyze the effect of different materials in the force and magnetic field and identify which are the best materials that yield maximum force.

1.1. Literature Review: Magnetic Levitation Vehicles

Magnetic levitation can be classified into two alternatives: Electromagnetic Suspension or Levitation by Attraction and Electrodynamic Suspension or Levitation by Repulsion.

1.2. Electromagnetic Suspension or Levitation by Attraction

This is the alternative elected in Germany and the vehicle is called Transrapid. The transrapid train has electromagnets on the railway and on the train. The railway electromagnets are placed on both sides of the railway and they are face to face with the train electromagnets. At both sides train and railway electromagnets are powered in such a way that current flows in the same direction which generates attraction forces between both electromagnets. As a result the train is pulled up. Just before the electromagnets touch each other, the energy is removed allowing the train to return to its normal position. This process is done approximately a hundred thousand times per second being controlled by a sophisticated electronic system which stabilizes and keeps the train in safe position at the same time a gap of 10 mm is generated [2,9].

With the objective of lateral stability the German train uses a rail, called guidance rail on each side of the railway structure. This rail does not contain electromagnets, since these are placed on the structure of the train in such a way that they face the guide rail and generate a force of attraction that is counteracted by the same phenomenon to the opposite side of the train providing the necessary lateral stability. Figures 1.2 and 1.3 illustrate this technique and its differences with conventional trains.

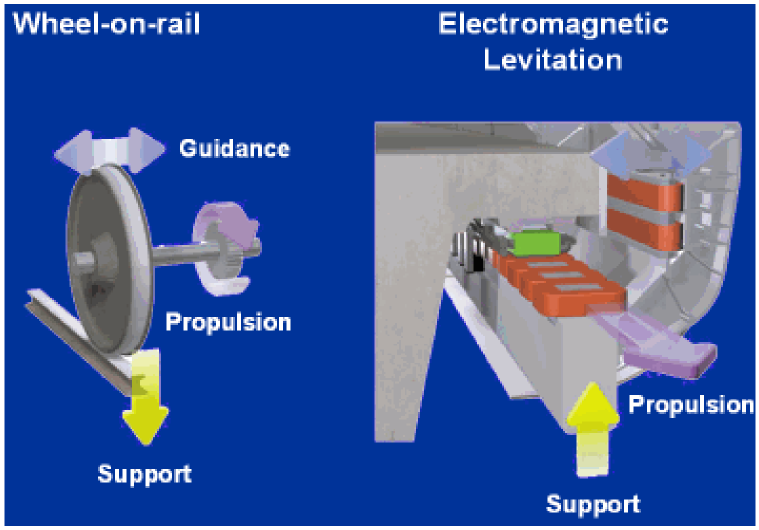


Figure 1.2. Comparison of Propulsion and Guide Mechanisms of Conventional Trains and Transrapid [10].

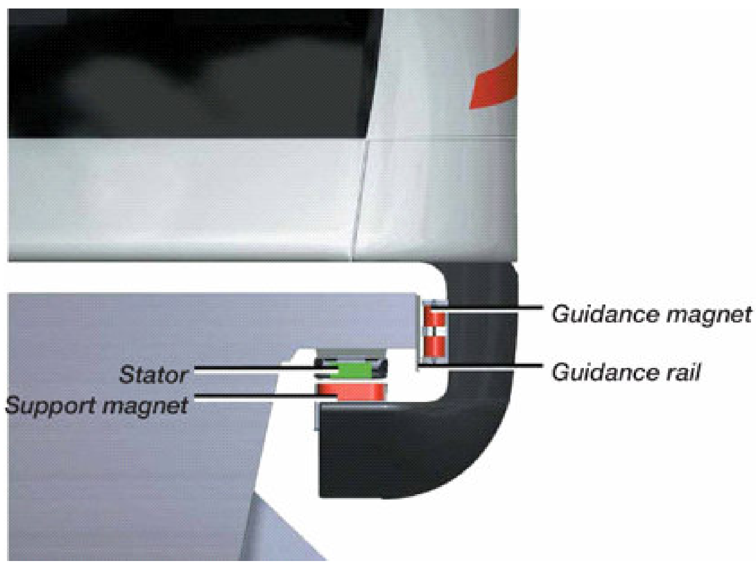


Figure 1.3. Transrapid Configuration [10]

The propulsion mechanism of this train consists of windings that act in similar way to the stator of a conventional motor; the train electromagnets can be seen as the rotor. Powering the windings with a three-phase current is possible to generate a traveling magnetic field whose speed is related to the frequency of the three-phase current and it is responsible for the movement of the train [9]. The propulsion windings are located in the railway and although they are through the whole railway, for energetic efficiency, only the part located below the train is powered [11]. As braking mechanism, the current polarization is changed causing the braking of the train [11]. Depending on the characteristics of the land or the technical improvements made with the continuous research, the configuration of the train could vary.

1.3. Electrodynamic Suspension or Levitation by Repulsion

This is elected as the Japanese alternative and is based on electromagnetic induction. The superconductor electromagnets on both sides of the train pass through the front of a series of conductor structures with the shape of an "eight", called levitation coils. The displacement of the magnetic field emanating from the superconductor electromagnets induces a current in the levitation coils and this in turn produces a magnetic field that, according to the Lenz's law, opposes to the change that created the induction generating this way the magnetic levitation [12].

The on board electromagnets must pass some centimeters below the center of the structure in form of "eight" and this in fact causes that the change of flow in the inferior half be bigger to that of its superior counterpart. The induced current in the inferior part presents such sense that the field generated for it opposes to the on board electromagnet field creating an identical magnetic pole to the magnetic pole in the electromagnet guaranteeing this way the repulsion on each other [12]. The form of eight of the levitation coils, allows to the induced current to change the sense in the superior part and a magnetic pole opposite to the one in the mobile electromagnet is generated and as a result attraction forces take place. This together with the attraction and repulsion generated in opposite sides of the train allows the levitation. The Figure 1.4 shows the superconductor magnet.

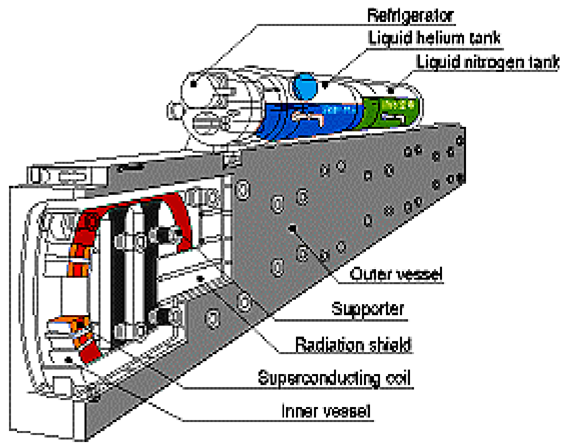


Figure 1.4. Superconductor Electromagnet [12]

As a guide mechanism the Japanese engineering has proposed to interconnect, through and under the railway, the levitation coils that are opposite to each other and the interconnected pair is called guidance coil. In accordance to the lenz's law, the displacement of the superconductor will induce a current that generate an opposite magnetic field. the levitation coil closer to the train in that moment experiments repulsion and the levitation coil far away experiments attraction, all this tends to hold the train in its normal position reaching stabilization [13, 14]. The mechanism of propulsion of this train is based on additional coils called propulsion coils. These coils are also located in the railway and they are energized with a three-phase current that creates a traveling magnetic field generating alternate magnetic poles. In this way between the propulsion coils and superconductors repulsion and attraction is generated and movement is reached.

As a consequence of the obligatory displacement in order to generate levitation the Japanese train must contain a motor of a conventional train.

At the moment Japanese engineering manage three forms of implementing the ground coils in the railway for the conventional motor that in turn should contain, levitation and propulsion coils.

1.3.1. Beam Method

This method will consist of building the sidewalls of concrete beams and install the levitation, ground and propulsion coils inside. This structure will be built at the on-site factory where the ground coils will be installed. The finished bean will be transported to the work site within the railway, to be placed in two platforms of concrete previously built [12].

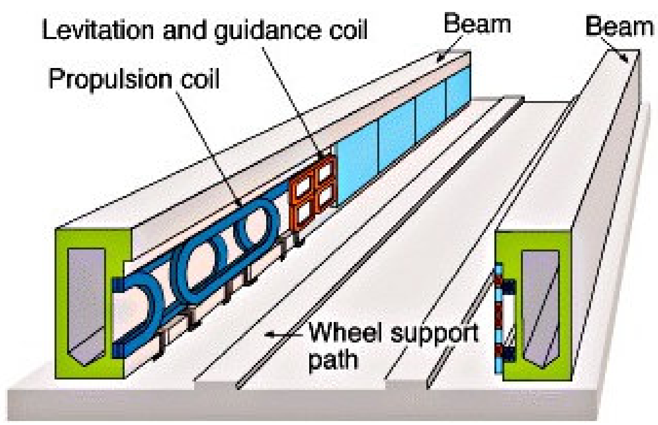


Figure 1.5. Beam Method [12]

1.3.2. Panel Method

In a factory set up on-site the concrete panels are built and the ground coils are installed. The finished structure is transported to the working place for being fixed with 10 bolts in the previously constructed sidewalls [12]. This method is shown in Figure 1.6

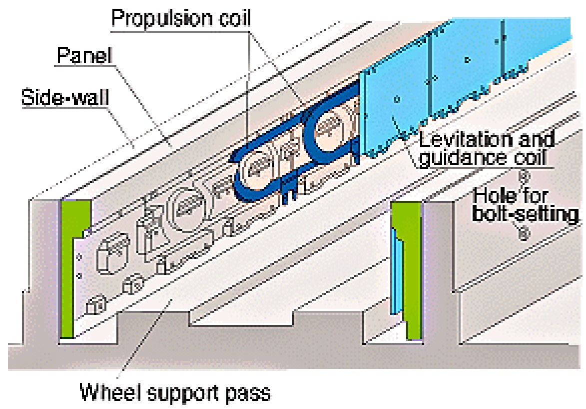


Figure 1.6. Panel Method [12].

1.3.3. Direct-Attachment Method

At the working place a portion of the lateral walls of concrete will be built and in the same place the finished walls are directly conditioned with the ground coils. This method is more economic because there is no necessity of transporting the levitation and propulsion coils. As disadvantage this method just allows slight adjustments in the ground coils in order to correct irregularities [12].

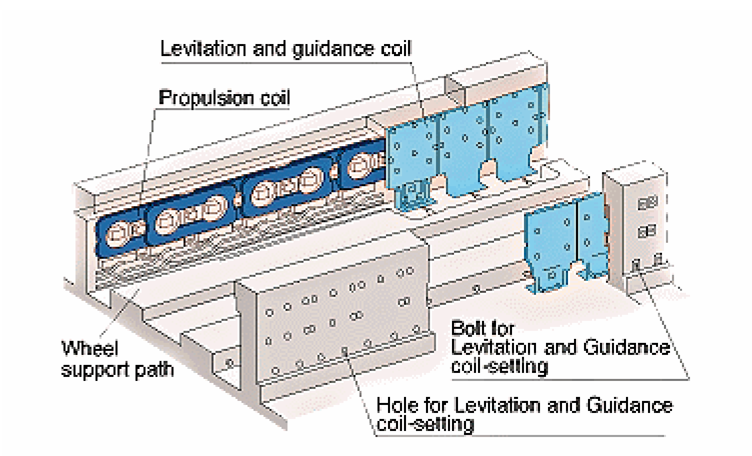


Figure 1.7. Direct-Attachment Method [12]

1.3.4. New Method

After an evaluation of the three methods (or three types of sidewalls) a new method was developed. This new method is intended to take the merits of the three methods besides of reducing costs. The essence of this method is the efficiency in installing the sidewalls to concrete roadbed in order to reduce the cost in the construction stage and maintenance. Among other alternatives an inverted Tee was adopted as shown in the following figure.

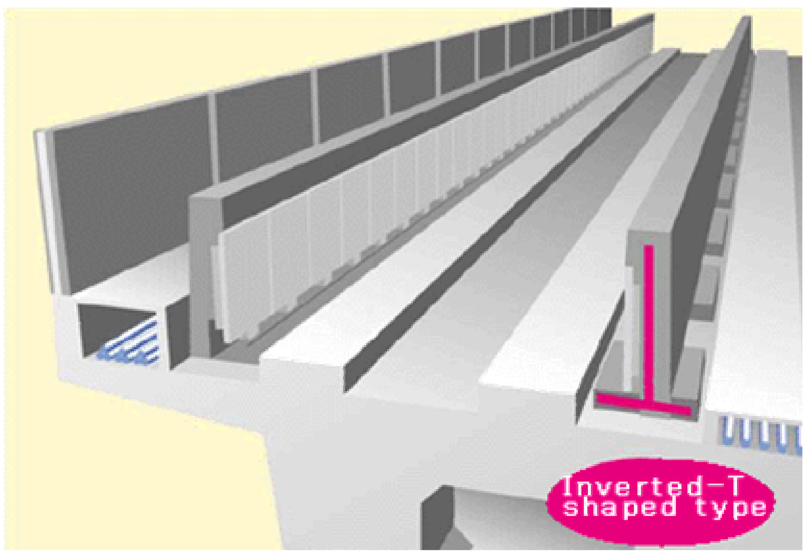


Figure 1.8 New Method [12]

1.4. Comparison between German and Japanese Alternatives

The german alternative is an active type levitation and it can levitate being at rest. When there is not power the train can not levitate and must be supported by special wheels.

The Japanese alternative is a passive type of levitation and needs movement between the on-board electromagnet and levitation coils. For this it requires wheels and a conventional motor which are essentials for reaching the transition speed, speed at which the levitation mechanism is generated, for the Japanese case this speed is 130 Km/hr [13].

For the Japanese alternative and their German counterpart the “motor” is in the railway. This motor type is known as lineal motor and represents great advantage regarding the conventional trains because these should overcome the inertia of its own weight and machinery.

1.5. Economic and Technical Implications

Superconductors have been broadly used for achieving magnetic levitation. These materials are used in the construction of the on-board electromagnets of the Japanese train and they present two basic characteristics: zero resistance and diamagnetism.

The zero resistance characteristic eliminates the energy losses, enhancing the efficiency. Zero resistance just can be reached, in principle, reducing the material temperature until a temperature denominated critical temperature. The temperature depends on the type of material and in order to reach it, requires the use of different substances for cooling, being liquid nitrogen a relatively common one. Investigations with the objective of achieving a more efficient economic operation have been developed. [15].

Diamagnetism is the ability of a material to repel a magnetic field. Diamagnetic materials present a relative permeability less than unity. In the case of superconductors the diamagnetism is strong below the critical temperature and this makes them to repel in a strong way an external magnetic field.

These characteristics have made obligatory the use of superconductor materials for the magnetic levitation in the Japanese case, since it is required to achieve levitations bigger than 80 mm, in order to satisfy safety standards in case of earthquakes at speeds of 500 Km/hr [4]. Conventional electromagnets could not reach the same performance due to the energy losses and to the necessary size. Due to the capacity of the superconductors for generating big fields is necessary the use of a shield system for passenger safety [11].

1.6. New Alternatives: Berdut Design and Inductrack

The previous alternatives present high inherent costs because of the use of superconductors and their corresponding cooling system. The necessity of powering the system to generate levitation and the inherent instability that makes complex the design of the control systems and imposes great demands on the quality to the electromagnets [16] are also drawbacks.

The Berdut design [5-8] makes use of permanent magnet levitation as a mean to overcome the limit of speed, with the advantage of generating levitation without power. The levitation is passive using permanent magnets in a configuration shown in Figure 1.1 whose effectiveness makes possible the concentration of the magnetic field generated by the magnets. This same principle is used in the propulsion mechanism. The levitation is also achieved by means of arrangements of permanent magnets on both sides of the railway [5-8], which is the arrangement responsible for the propulsion.

To use permanent magnets in a magnetic levitation vehicle several conditions must be satisfied [17]:

- The levitation should be inherently stable with the objective of avoiding the use of control circuits.

- The weight of the magnets must be relatively small in comparison with the weight to levitate.

- The drag should be the sufficiently small to satisfy the cost-benefit requirements.

The previous characteristics are fully met by the magnetic levitation alternative developed by Berdut. At the present time another project favored by NASA exists and is carried out at the Lawrence Livermore National Laboratory which has already run tests and investigations with the objective of demonstrating the operative and economic viability of this new concept in magnetic levitation. This new alternative uses permanent magnets prepared in a special configuration called Halbach array whose main characteristic is to concentrate the magnetic field, increasing its efficiency [3, 16-19]. At the moment this alternative has just been proven with scale models and it is in fact the most similar alternative to the levitation concept used in the Berdut alternative. This forces to carry out a detailed exploration of the current state, results, feasibility etc of this new alternative.

The alternative presented by the Lawrence Livermore National Laboratory has received the name of "Inductrack" due to the current induction on the track, the idea initially arose of investigations in electromechanical batteries, which store kinetic energy making use of a wheel that had magnetic bearings with almost no friction. These bearings use arrangements of cylindrical magnets to stabilize the levitation of the wheel. When unrolled, these stabilizers are the whole basis for the Inductrack [18].

The Inductrack uses a rectangular arrangement of permanent magnets called Halbach array [20] in honor to its inventor Klaus Halbach (1925-2000). The magnetic orientation of each magnet is perpendicular with the adjacent one, the arrangement has the property of canceling the magnetic field in one side and to concentrate it on the opposed side which produces a strong magnetic field in that side. The permanent magnets used in the Inductrack are built of an alloy of Neodymium, Iron and Boron (NdFeB) [3] which is able to generate a considerable magnetic field. The following figure illustrates the configuration of a Halbach array.

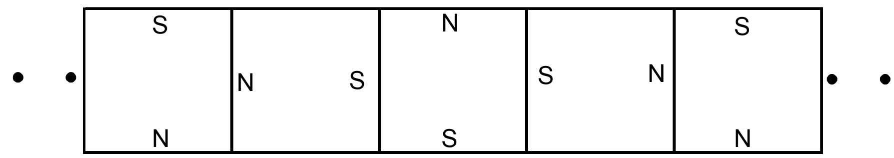


Figure 1.9. Halbach Array

The Halbach arrays are installed in the inferior part and to both sides of the supporting vehicle, as illustrated in Figure 1.10

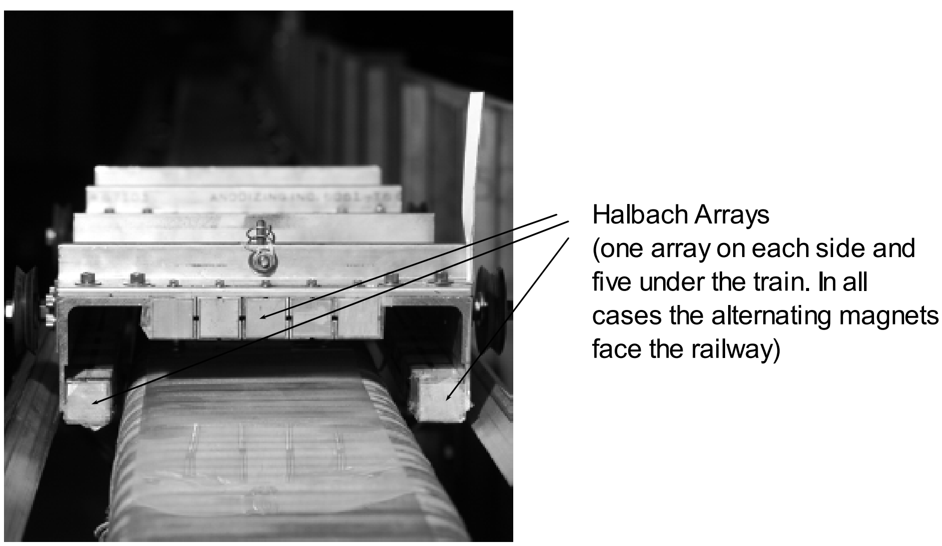


Figure 1.10. Inductrack Scale Model

The other key element besides Halbach array is the track, which is made up of an arrangement of rectangular windings where each one is a closed circuit. The speed of transition, this is the speed where the levitation is reached, it is approximately 2 m/s. [3]. The magnetic field, between the train and the railway, in this case acts as a compressed spring: the levitation force is increased exponentially when the separation between the vehicle and the track decreases, this property is the responsible for the inherent stability of the Inductrack.

For levitating, the Inductrack needs to induce currents in the circuits of the tracks and due to the resistance of the cables power is dissipated in the form of heat, (I^2R) which as consequence increases the drag. This drag force is the magnetic counterpart of the drag due to friction between wheels and rail in a conventional train. In the Inductrack the magnetic drag varies inversely with the speed of the train, being low at speeds from 250 to 500 km/hr [18], this makes that these forces behave in an inverse way to the aerodynamic and friction forces since these increase with the speed.

With a train weighing 50000 kilograms and traveling at a speed of 500 km/hr, approximately 300 to 600 Kilowatts of power would be dissipated in the track levitation circuits. The aerodynamic drag at that velocity would cause a loss of power of 10 Mwatts [18], meaning that the power needed to maintain the train levitating is smaller than one tenth of that required to overcome the aerodynamic load.

With the objective of increasing the efficiency, the track can be using one of two alternatives:

— Several thin sheets of aluminum heaped with sealing films between them. When the array moves above them the magnetic field will induce electric currents in the sheets and by means of parallel slots in each sheet a good path would be created for the electrons, minimizing the eddy currents that would increase the lost of power, this alternative would increase the levitation force and would be cheaper [18].

— Using the inductive loading method which places thin ferrite sheets around the base of each winding, this reduces the induced current in those coils due to the array. The loss of power in coil of the tracks is reduced because of the magnetic drag would be low, the magnetic lift would act at smaller speeds and the train would levitate at smaller speeds [18].

The scale model built at the moment uses the second alternative and the windings of the track have the following characteristics: 15 centimeters wide, the cables measure 20 meters long, the numbers of turns is 53 and the diameter of the cable is 0.2032 cm. The array is inductively loaded on the superior and inferior part with ferrite sheets [3]. In both sides of the arrangement and parallel to each other are located some aluminum rails that support the auxiliary wheels of the cart when it is not levitating. Figure 1.11 illustrates the track windings.

The two new alternatives present common advantages:

— Elimination of the superconductors and their cooling system, which generates an important cost reduction.

— Elimination of the complexity in the design as a consequence of the inherent stability mechanism of the two alternatives.

— With the use of permanent magnets the maintenance costs are reduced.

— The use of passive levitation generates a reduction in the operating costs and with an appropriate selection and manipulation of the materials is possible to increase the efficiency.

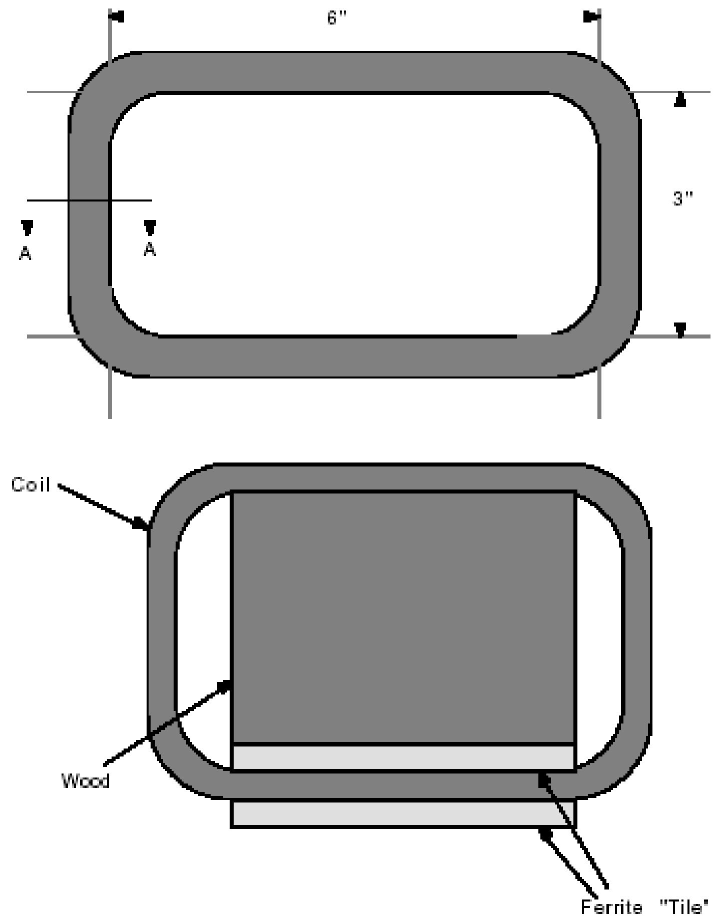


Figure 1.11. Inductrack Windings

In a same way fundamental differences are presented:

— The Inductrack has the propulsion and levitation mechanisms in the same rail. In this project the levitation mechanism is also generated by means of the permanent magnets configured in Halbach arrays located side to side on the rail in which the permanent magnets responsible of propulsion are also located.

— The inductrack needs speed for levitating, although it is small, this requires to a conventional motor and wheels to reach this speed.

— The Berdut train also uses wheels but these act just as backup support for safety in the event of curves and high speed.

1.6.1. Comparison between the two Geometries

In the following figures the geometric configuration for the Inductrack and Berdut train are presented. A 3D and 2D magnetic view is shown in order to present a detailed description of each geometry.

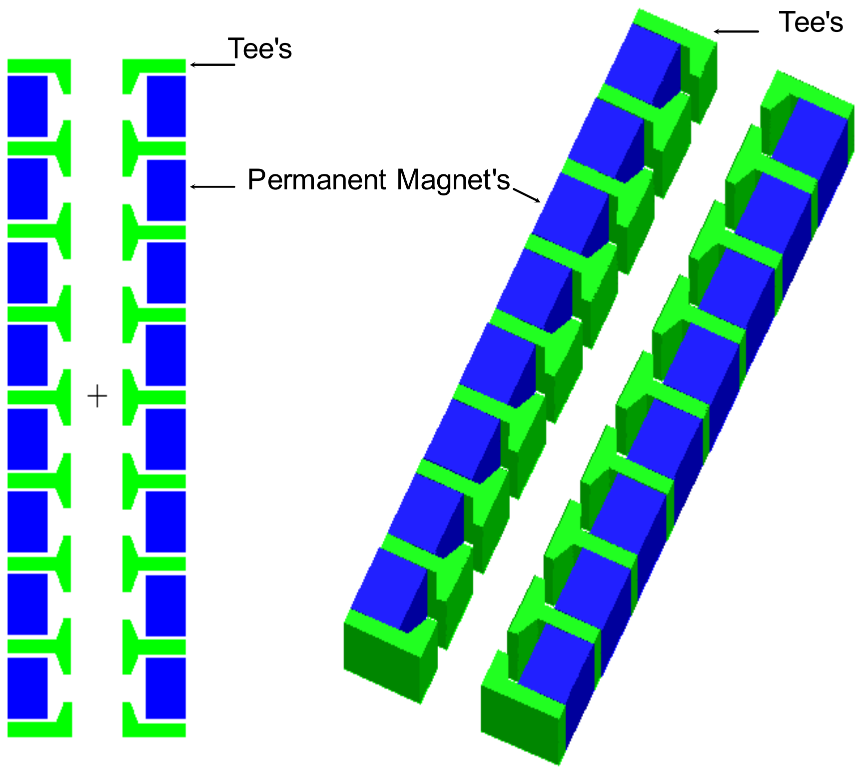


Figure 1.12. Geometry Configuration of Berdut Train (propulsion)

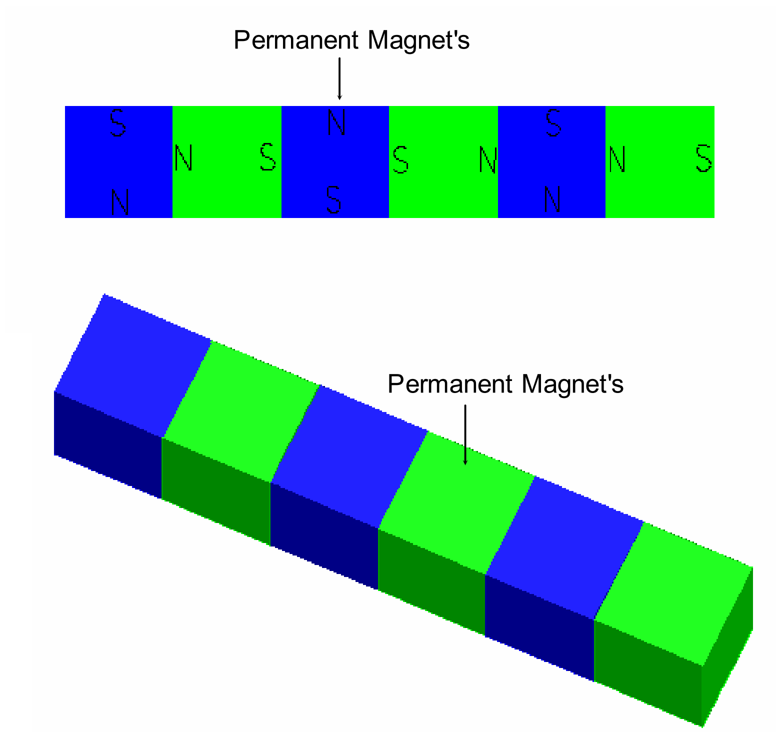


Figure 1.13. Halbach Array Geometry. 2D and 3D Views

In order to clarify the physical differences between the two geometries are generated some simulations using the program Maxwell 2D version 9. As previously mentioned, the field concentration effect is a common element in these two geometries and this effect is fundamental and indispensable for propulsion. The concentration effect will be demonstrated by means of computer simulations. Despite of the common concentration effect the two geometries are completely different.

In the following Figures the simulation results are shown using a plot of flux lines. In Figure 1.14 the magnetization direction of the permanent magnets is illustrated. The magnetization direction of one permanent magnet is perpendicular with the adjacent magnet and presents a clockwise direction. For this case the magnetic field is concentrated as illustrated in Figure 1.14

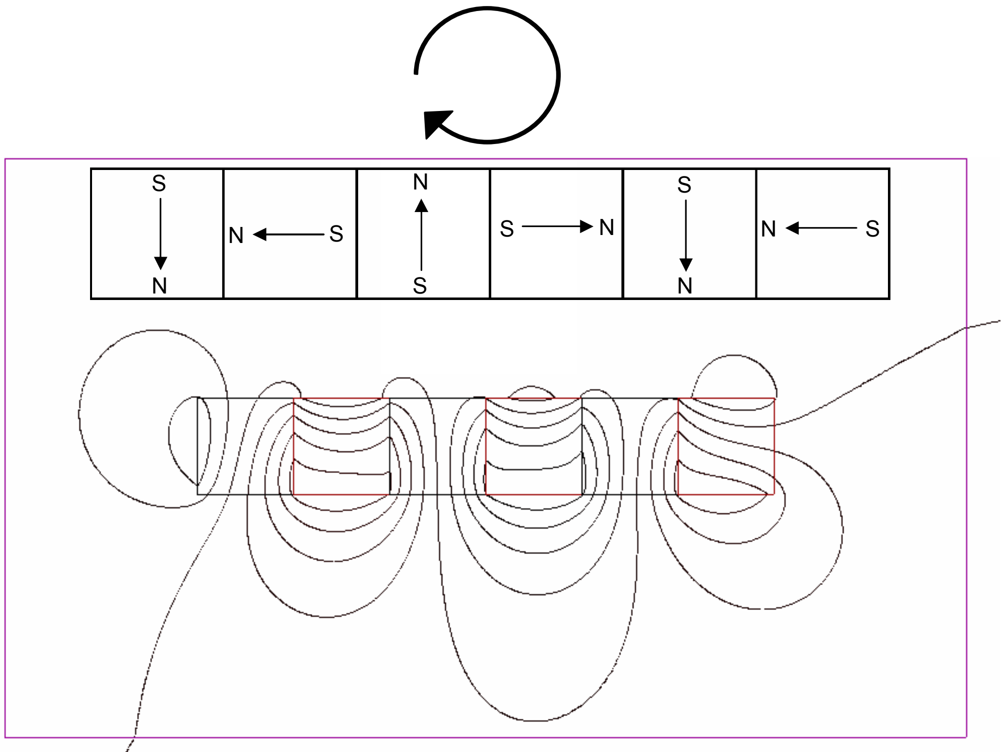


Figure 1.14. Flux Line Plot for Halbach Array

When the vehicle moves in the track, the induction current generated, thanks to the magnetic field concentration, creates repulsion and therefore levitation. Due to the elimination of the magnetic field in the top part, the shielding for protecting the passengers from magnetic fields is not a critical factor constituting a cost reduction.

In the case of Berdut design, in Figure 1.15 the field is concentrated at the center of the arrangement and specifically at the Tee's. This concentration effect is caused by the ferromagnetic characteristics of the material of the tee’s and increments the magnetic field. This concentration toward the center implies a reconfiguration of the magnetic field eliminating it in both exterior sides of the geometry. In the center of this geometry a series of windings are inserted as seen in Figure 1.16. These windings are installed in the train. Powering these windings in such a way that the interaction generated between the winding’s magnetic field and that on the geometry creates a force over the winding that in turn generates a movement whose sense will depend on the current polarization in the winding. The current sense controls the sense of the movement, the speed and the braking system.

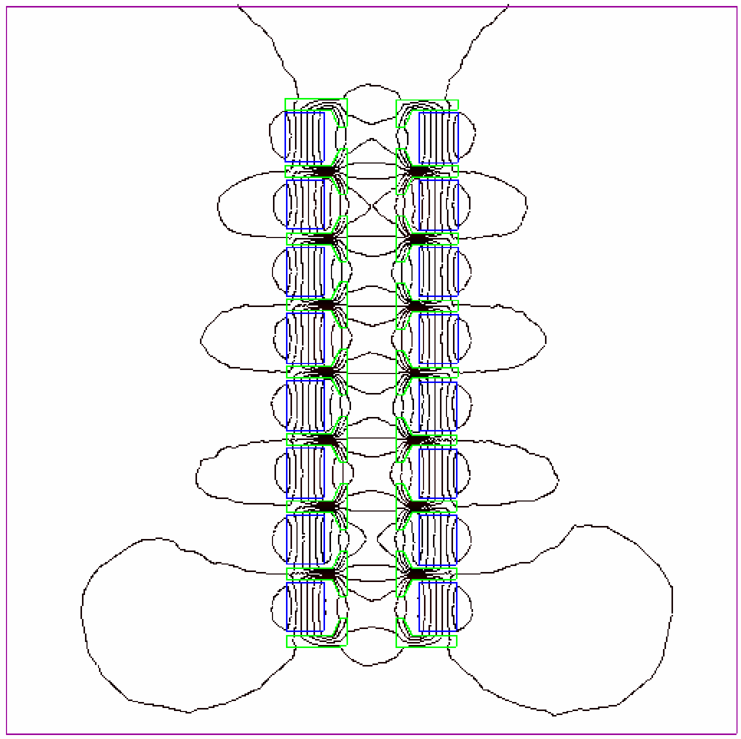


Figure 1.15. Flux Lines Plot for Berdut Configuration

Figure 1.16 shows a portion of the total Berdut design including the on-board windings, tee's and permanent magnets. The windingcore illustrated in Figure 1.16 is a very important element in the configuration because its material can concentrate the magnetic field incrementing it. The windingcore is moving through the configuration. this means that in any point the windingcore is concentrating the flux lines and this in turn always increment the magnetic field causing a reconfiguration of magnetic field around the windingcore. The reconfiguration of magnetic field imparts a big difficulty in the theoretical prediction of the force and its behavior. All this justifies the use of software programs in order to decipher the relation between force and magnetic field and the interaction between the components of the geometry. The portion illustrated in Figure 1.16 will be a standard for the simulations however the number of tee and permanent magnets can be different. The materials and current polarization of the winding will be varied in order to achieve the largest force magnitude.

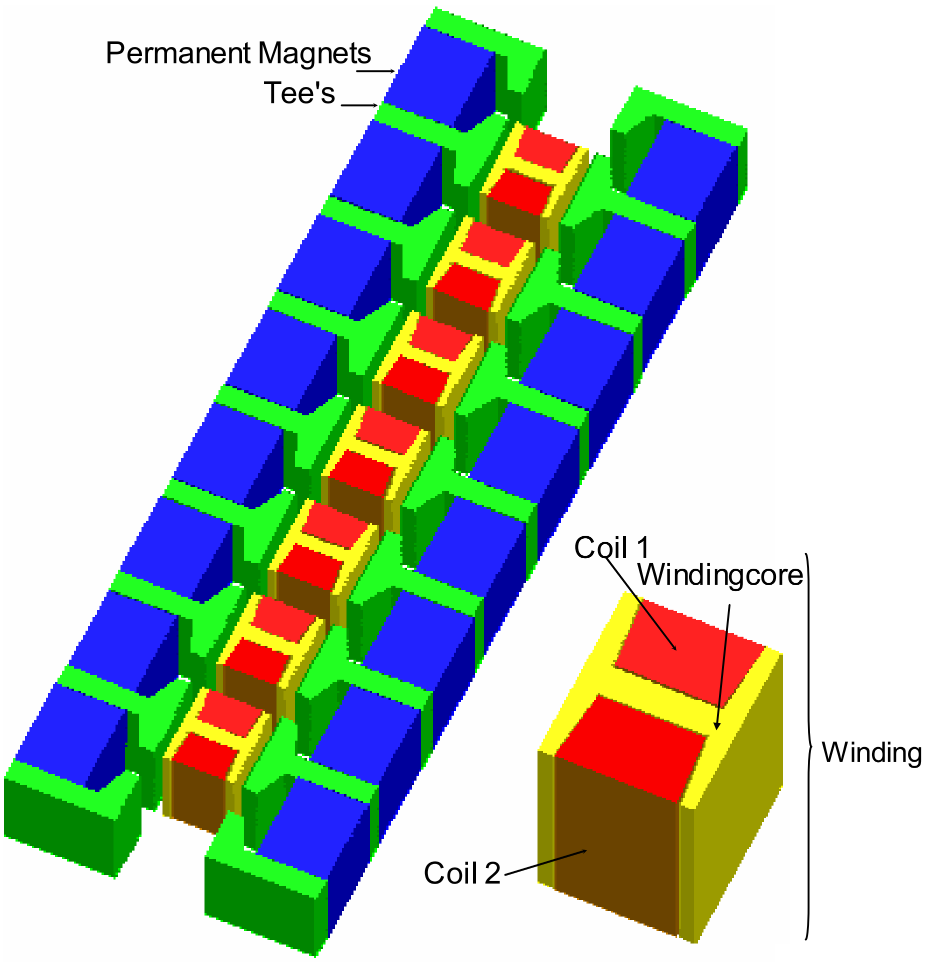


Figure 1.16. Total Geometric Configuration of Berdut Design

Due to software limitation of Maxwell 2D a winding can not be simulated as loops of currents. The winding in this thesis will be simulated as solid blocks of copper. This limitation will cause a difference between the real force and the simulated force.

In Chapter 2 a set of simulations will be run with the objective of exploring the effects and operation of each component of the geometry in order to understood how is the magnetic behavior of this alternative.

Chapter 2

Methods and Materials

The components of Berdut design are permanent magnets, tee's or poles, and windings. The magnets generate a magnetic field that is concentrated in the tee's thanks to its material. The interaction between this magnetic field and the one due to the windings generates a force. Maxwell 2D version 9, available at University of Puerto Rico is not able to run a type of simulation where a change in current polarization is applied simultaneously to the winding as it pass through the magnetic field. Without this analysis factors like velocity and acceleration can not be connected with the force generated in the configuration and the total effects of the force cannot be analyzed. For all this the following analysis will be focused on the function of each component of the Berdut design and how the number of elements or their position can affect the magnetic field and the force. In this chapter, through a set of simulations the importance, function and influence of each component will be described together with how they affect the magnetic field in magnitude and direction. Also the global behavior of the Berdut design will be discussed

2.1. The Berdut Design

In this chapter first the magnetic field of a permanent magnet will be analyzed then the effect of adding a tee will be described, next a second permanent magnet will be added with magnetization direction correlated with the first permanent magnet. A mirror copy will be added to this configuration with the correct magnetization direction in the permanent magnets. After all this, pairs of tee's will be added to the array until the final configuration is achieved where the winding will be inserted and an analysis of force will be introduced. All simulations were done using Maxwell 2D Version 9 with an error percent of 0.5 % the convergence criterion was to iterate until a 0.5 % error between the force calculated for the current iteration and previous was obtained. The dimensions were recommended by Mr. Berdut and the patents.

2.1.1. Magnetic Field of a Permanent Magnet

The Figure 2.1 shows the dimensions, B field, and the flux lines of a rectangular permanent magnet. The behavior of the magnetic field is well known in this case. The magnetic field forms a close loop that starts in north pole and ends in the south pole and it is symmetric. The material of the permanent magnet in this case is ceramic5.

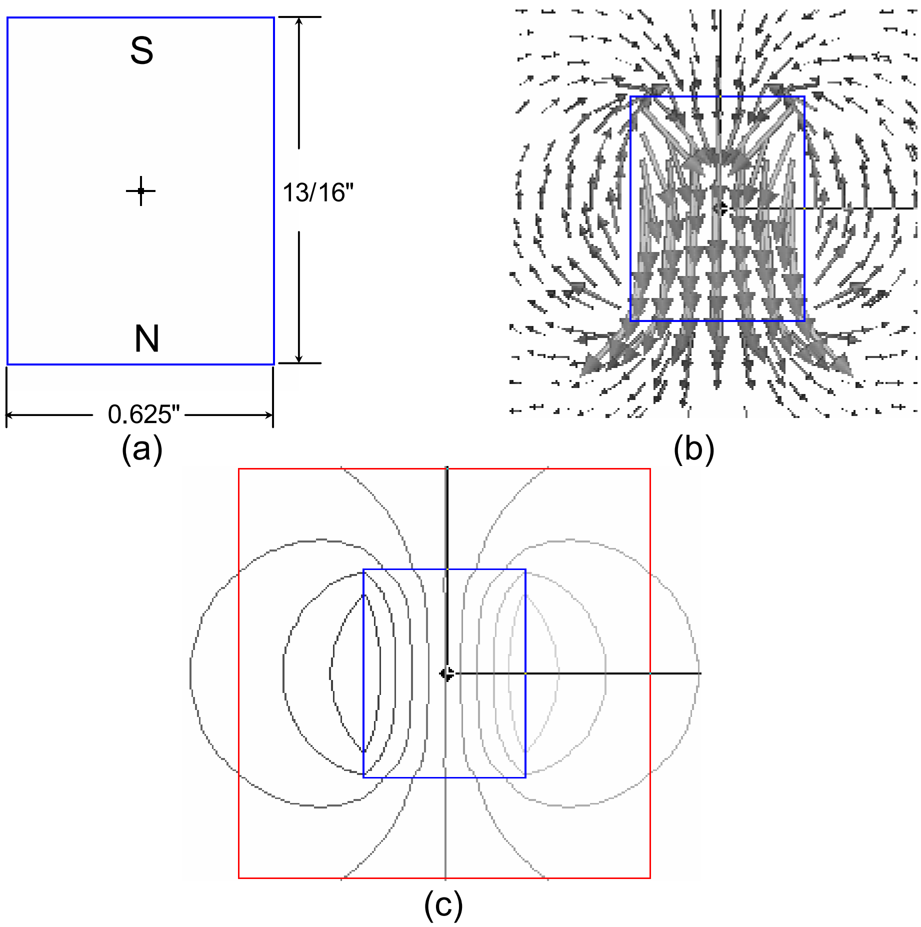


Figure 2.1. Permanent Magnet Simulation (a) Magnetization Direction, (b) Magnetic Field, (c) Flux Lines.

Table 2.1. Magnetic Field Magnitude for a Ceramic 5 Permanent Magnet.

Region around the magnet	Magnetic field magnitude (T)
0.3" (0.7 cm)	2.5×10^{-1}
0.5" (1.3 cm)	7.2×10^{-2}
0.7 " (1.7 cm)	3.6×10^{-2}
0.8 " (2 cm)	3.9×10^{-2}

2.1.2. Tee and Permanent Magnet

When a Tee of cast iron is set besides the permanent magnet of Figure 2.1, a concentration effect takes place and the magnetic flux is incremented. This configuration will be named configuration 1. Cast Iron is easy to magnetize and demagnetize. The molecular magnets in the tee are oriented in the same direction of the magnetic field generated by the permanent magnet reinforcing it. The concentration effect depends on the materials used for the Tee's. In Figure 2.2 this configuration is illustrated. The separation between the tee and the permanent magnet is 0.001 inches (0.0254 mm) as indicated in Figure 2.3. This separation is the minimum gap tolerated by Maxwell 2D.

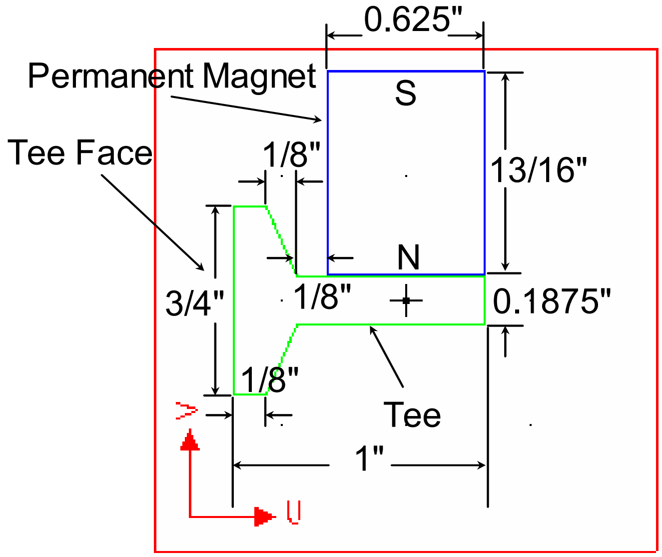


Figure 2.2. Permanent Magnet and Tee Configuration.

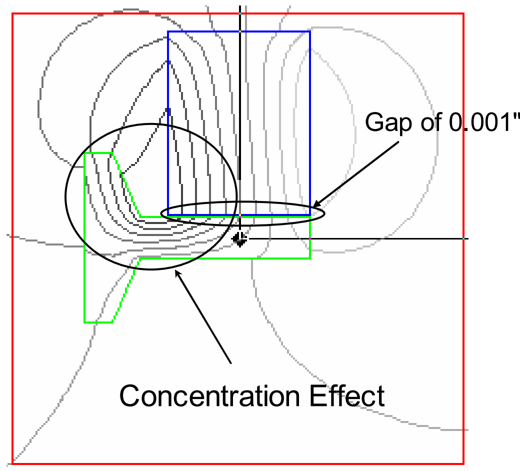


Figure 2.3. Concentration Effect. Configuration 1.

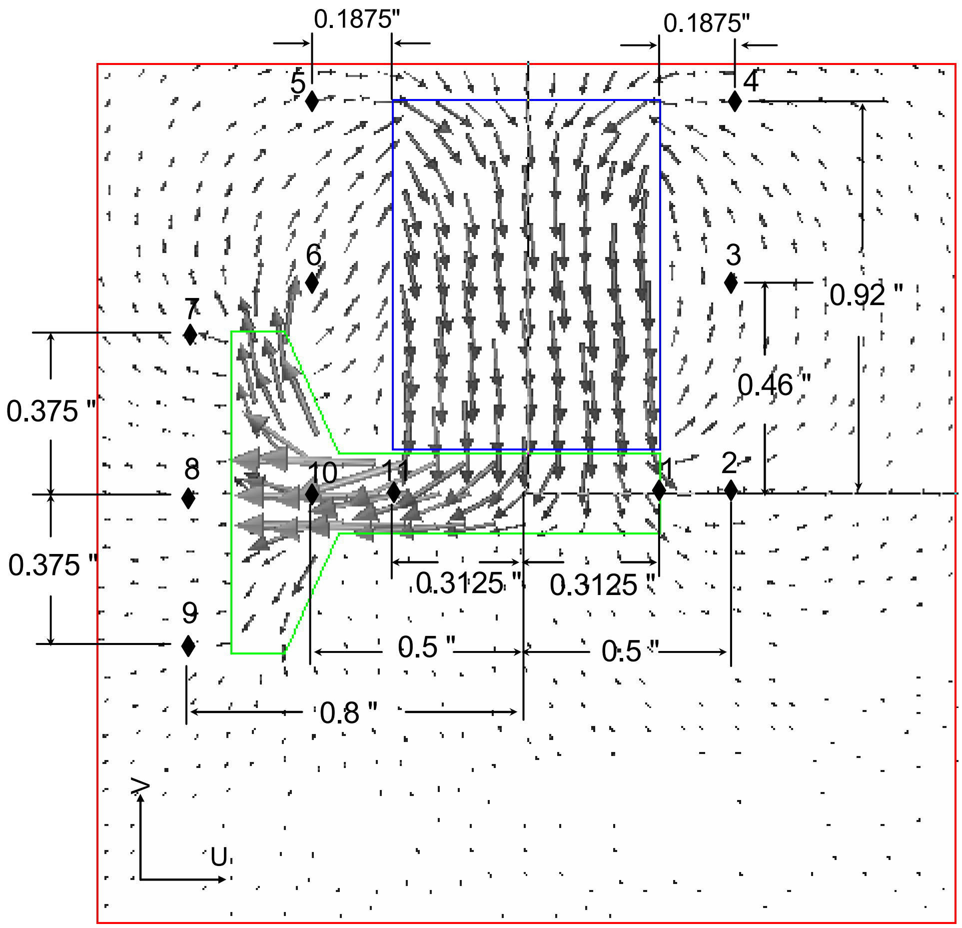


Figure 2.4. Magnetic field. Configuration 1.

In Figures 2.3 and 2.4 it can be observed the concentration effect and how the magnetic field is being oriented towards the tee face. Some points are also listed and the value of the magnetic field in these points is in Table 2.2. The points 10, 6 and 5 are geometrically symmetric to the points 2, 3, and 4, the point 1 is geometrically symmetric to point 11.

Table 2.2. Magnetic Field Magnitude. Configuration 1.

Point around the Configuration 1	Magnetic field Magnitude (T)
1	9.3×10^{-2}
2	9.3×10^{-2}
3	9.3×10^{-2}
4	9.3×10^{-2}
5	9.3×10^{-2}
6	1.9×10^{-1}
7	9.3×10^{-2}
8	5.1×10^{-9}
9	5.1×10^{-9}
10	6.5×10^{-1}
11	5.6×10^{-1}

Observing the points 1 and 11 in Figure 2.4 the concentration effect can be confirmed. These points are geometrically symmetric but the point 11 is in the concentration area therefore the magnetic field in this area is larger. The same occurs with the points 2 and 10. The points 6, 7, 8, 10 and 11 are in the concentration zone however the points 10 and 11 are also in the tee and the magnetic field is bigger due to the magnetic contribution of the cast iron. The points 7 and 8 are in the air surrounding the tee face and the magnetic field suffers a reduction (the flux lines are more separated) because the air is not as good flux conductor as the cast iron. If a second permanent magnet is added with the correct magnetization direction and position the magnetic field and concentration effect will be reinforced. This configuration will be named Configuration 2.

2.1.3. Configuration 2

The dimensions of Configuration 2 are showed in Figure 2.5. The separation between the permanent magnet and the tee is 0.001".

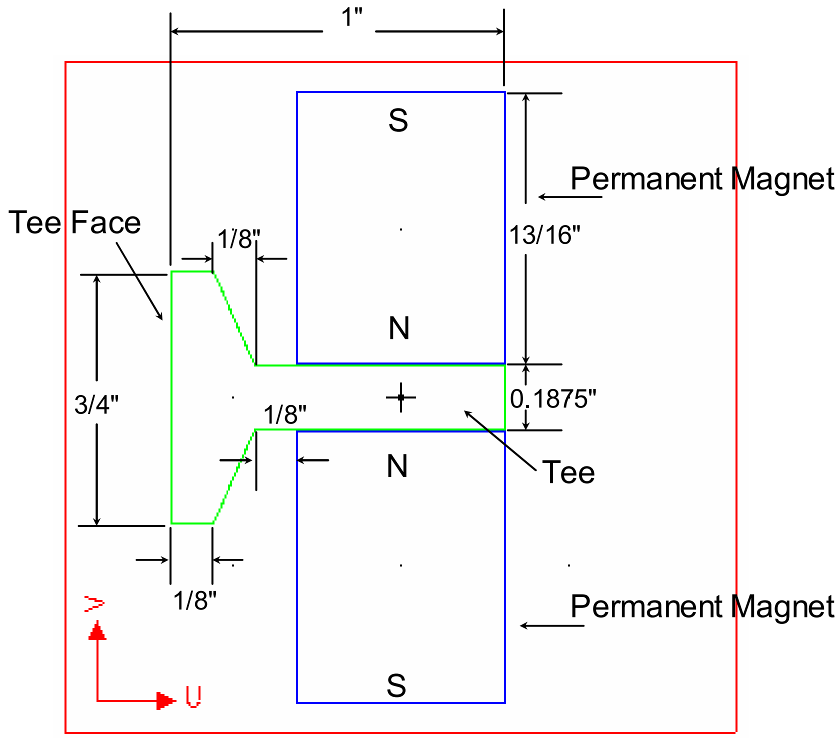


Figure 2.5. Configuration 2.

In this configuration the magnetization direction of the permanent magnets generates a "north pole" in the tee. This is demonstrated in Figure 3.7 where the magnetic field is presented. In this Figure the magnetic field starts in the tee (north pole) and ends in the south pole of the permanent magnet.

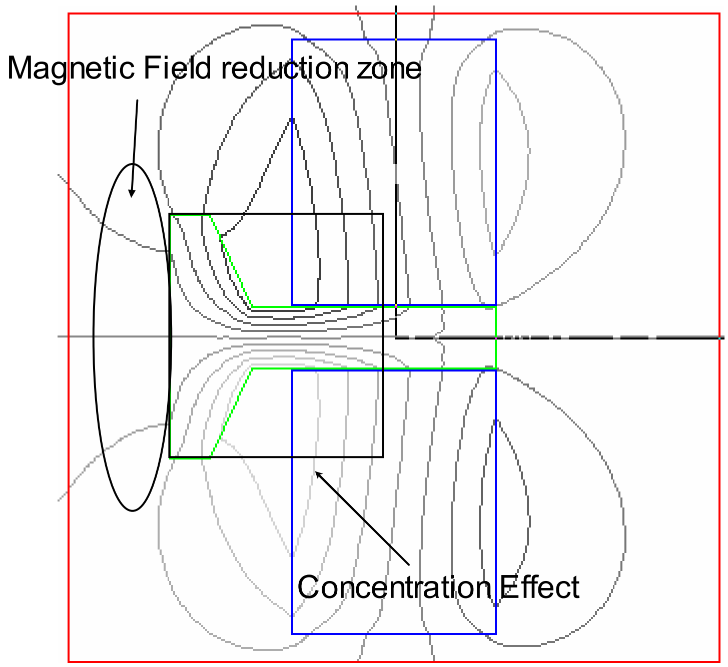


Figure 2.6. Flux Lines. Configuration 2.

As can be seen in Figure 2.6 the concentration effect is an important factor. The concentration of the flux lines depends on:

- The magnetization direction of the permanent magnets and the position of the permanent magnets.

- The shape in form of tee is important because the flux lines will trend to concentrate toward the region where there is more ferromagnetic material (the tee face). The material of the tee is also important because if better flux conduction can be reached the magnetic field will be incremented

The first two factors are associated with the configuration so the concentration effect can be optimized manipulating the configuration as will be demonstrated. Regarding the last factor a material with high relative permeability will concentrate much more the flux lines and this will augment the magnetic field and therefore the force.

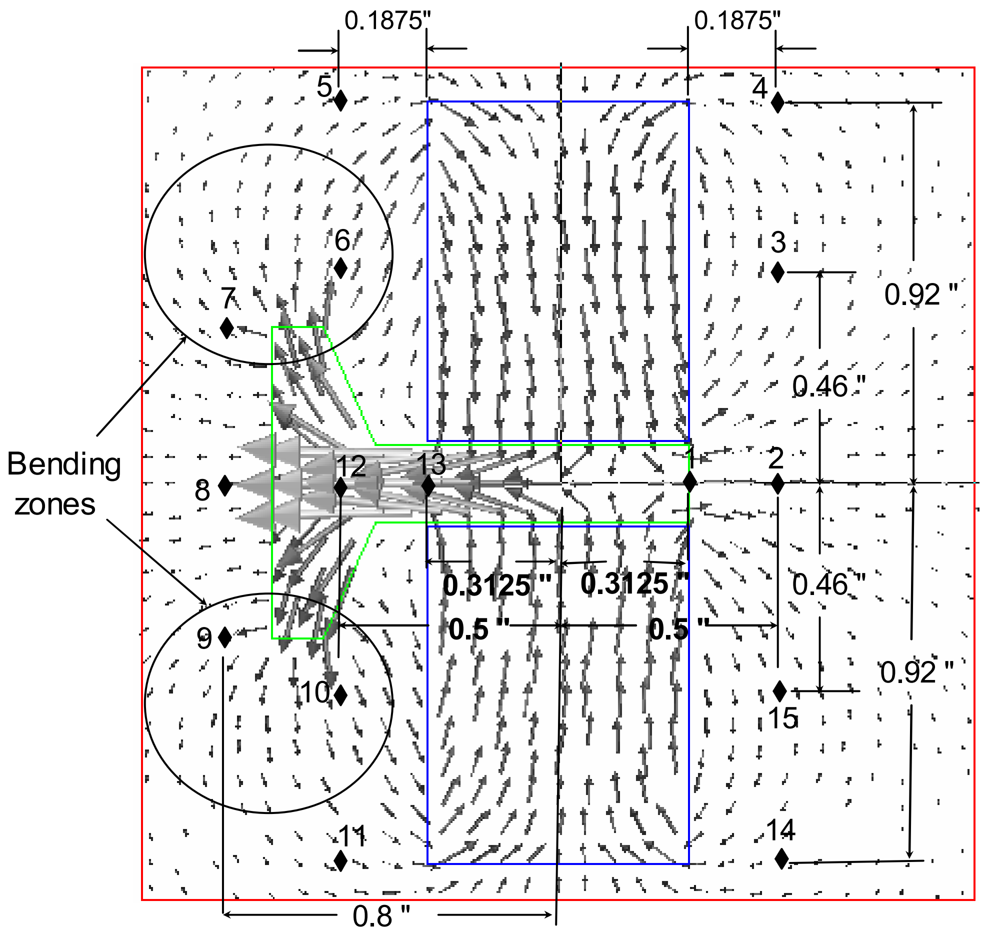


Figure 2.7. Magnetic Field. Configuration 2.

The Figure 2.7 confirms the concentration effect and reveals a bending effect. This effect is impossible to eliminate because is directly related with the edges of the configuration elements. In Figure 2.7 just two bending zones are indicated but in all edges there are bending zones, as can be seen in Figure 2.7. The bending zones represent a dramatic reduction in the magnetic field respect to the field in the tee's because they are in the air and the air is not as good flux conductor as cast iron, this can be confirmed in Figure 2.6. In the Bending zones a reduction in the magnitude force exerted over the winding can be expected.

In Figure 2.7 measure points are presented, the points 14, 15, 2, 3 and 4 are geometrically symmetric to the points 11, 10, 12, 6, 5 the points 1 and 13 are also geometrically symmetric. The magnitude of the magnetic field in these points is presented in Table 2.3

Table 2.3. Magnetic Field Magnitude. Configuration 2.

Point	Magnetic field Magnitude (T)
1	1.2×10^{-1}
2	6.9×10^{-10}
3	6.9×10^{-10}
4	6.9×10^{-10}
5	6.9×10^{-10}
6	1.2×10^{-1}
7	1.2×10^{-1}
8	1.2×10^{-1}
9	1.2×10^{-1}
10	1.2×10^{-1}
11	6.9×10^{-10}
12	9.5×10^{-1}
13	8.3×10^{-1}
14	6.9×10^{-10}
15	6.9×10^{-10}

Observing the field magnitude of the points 7, 8, 9, 12, 13, note that it is larger than the magnitude of their counterparts in Table 2.2 the points 7, 8, 9, 10, 11. The contribution of the second permanent magnet to the concentration of the flux lines is the cause of the difference in magnitudes for these points. A comparison of these magnitudes is made in Table 2.4.

Table 2.4. Concentration Effect. Configurations 2 and 1

Figure 2.7 point	**Magnetic Field Magnitude (T)**	**Figure 2.4 point**	**Magnetic Field Magnitude (T)**	**Percent of increment**
7	1.2×10^{-1}	7	9.3×10^{-2}	29
8	1.2×10^{-1}	8	5.1×10^{-9}	—
9	1.2×10^{-1}	9	5.1×10^{-9}	—
12	9.5×10^{-1}	10	6.5×10^{-1}	46.15
13	8.3×10^{-1}	11	5.6×10^{-1}	48.21

The points 1, 2, 3, 4, 5, 6 in Figure 2.7 are symmetric to the points 1, 2, 3, 4, 5, 6 in Figure 2.4 and a comparison of their magnitudes is made in Table 2.5.

Table 2.5. Symmetric Points. Configurations 2 and 1

Figure 2.7 point	**Magnetic Field Magnitude (T)**	**Figure 2.4 point**	**Magnetic Field Magnitude (T)**	**Percent of increment**
1	1.2×10^{-1}	1	9.3×10^{-2}	29
2	6.9×10^{-10}	2	9.3×10^{-2}	—
3	6.9×10^{-10}	3	9.3×10^{-2}	—
4	6.9×10^{-10}	4	9.3×10^{-2}	—
5	6.9×10^{-10}	5	9.3×10^{-2}	—
6	1.2×10^{-1}	6	1.9×10^{-1}	-36.8

In Table 2.5 the concentration effect is evident because points in the same position as points in Figure 2.4 present larger magnitudes than the corresponding points in Figure 2.7. This is because the concentration effect begins to eliminate the magnetic field to right of the configuration concentrating it towards the tee face resulting this in a reconfiguration of the magnetic field in magnitude and direction.

Regarding the uniform zone of Figure 2.7, the direction of the magnetic field in this zone is directly related with the “north pole” generated in the tee after the permanent magnets are fixed to both sides of the tee with the specific magnetization direction shown in Figure 2.6. If a configuration with exactly the same dimensions is set in front of Configuration 2 with a magnetization direction of the permanent magnets that generates a “south pole “ in the tee, the magnetic field will go directly to the tee face that represents the south pole. This new configuration in combination with Configuration 2 will named Configuration 3.

2.1.4. Configuration 3.

For this configuration the magnetization direction for each permanent magnet and the dimensions are described in Figure 2.8 the separation between the tee’s and the permanent magnets is 0.001 inches,

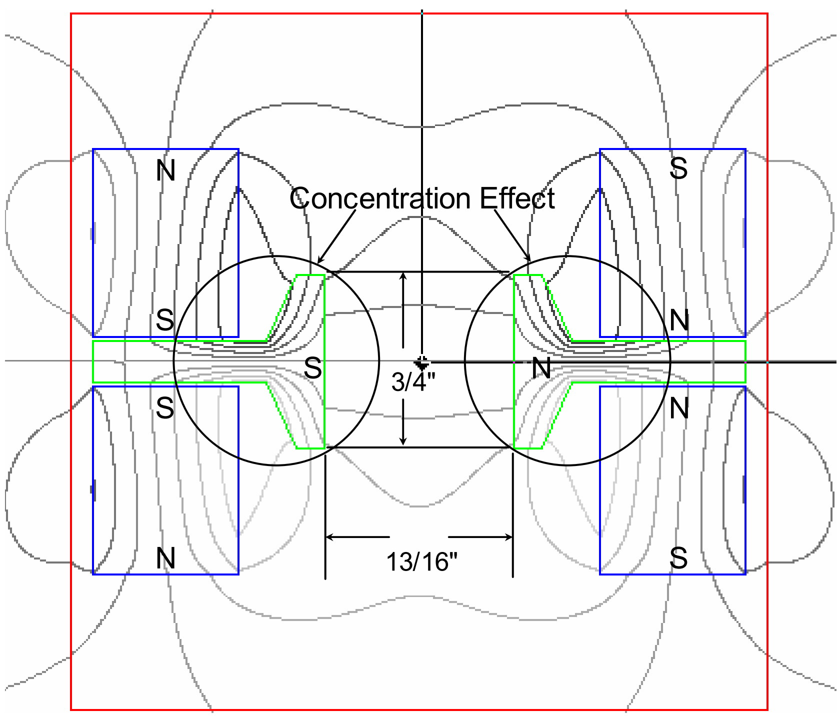


Figure 2.8. Flux Lines. Configuration 3

In Figure 2.8 the concentration effect is demarcated by the two circles. In this configuration the magnetic field is being reoriented toward the tee faces. In the zone between the tee faces the magnetic field will tend to go from north pole (right tee) to south pole (left tee) presenting a uniform direction. With the addition of the extra tee a feasible path for the magnetic field is established and flux lines begin to appear between the tee faces as can be seen in Figure 2.8. Another function of the tee's is to give uniformity to the direction of the magnetic field.

In Figure 2.8 a poor concentration of flux lines is observed between the tee faces due to the air and a reduction of the magnetic field is experimented in this zone. A trend to concentrate the magnetic field toward the center of the configuration is also perceived which represents an advantage when the winding is inserted.

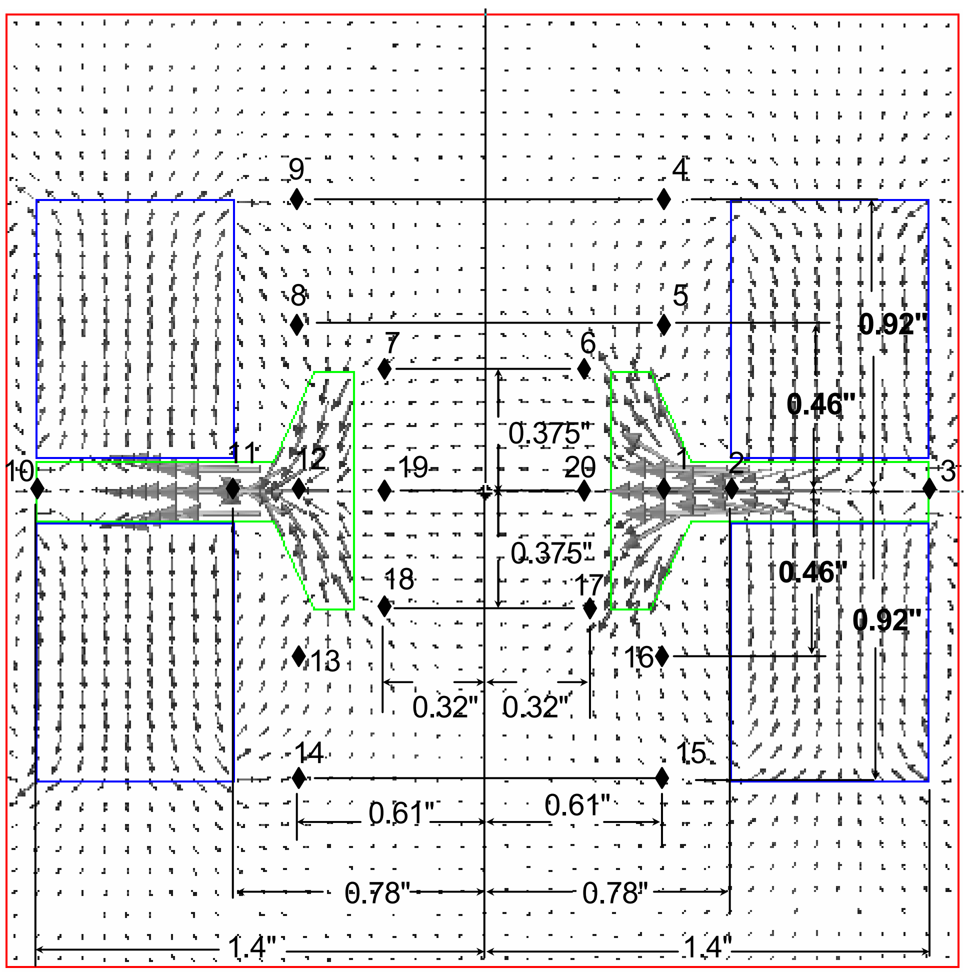


Figure 2.9. Magnetic Field. Configuration 3.

In Figure 2.9 the points 1, 4, 5, 16 and 15 are geometrically symmetric to the points 12, 9, 8, 13, 14, the points 2 and 3 are geometrically symmetric to the points 11 and 10, the points 6, 20 and 17 are geometrically symmetric to the points 7, 19 and 18. The points 1, 2, 6, 7, 11, 12, 17, 18, 19 and 20 are in the concentration zone. The value for the magnitude of the magnetic field in all points is given in the next Table.

Table 2.6. Magnetic Field Magnitude. Configuration 3.

Point	**Magnetic field Magnitude (T)**
1	1.02
2	8.8×10^{-1}
3	1.47×10^{-1}
4	5.8×10^{-11}
5	1.47×10^{-1}
6	1.47×10^{-1}
7	1.47×10^{-1}
8	1.47×10^{-1}
9	5.8×10^{-11}
10	1.47×10^{-1}
11	8.8×10^{-1}
12	5.86×10^{-1}
13	1.47×10^{-1}
14	5.8×10^{-11}
15	5.8×10^{-11}
16	1.47×10^{-1}
17	1.47×10^{-1}
18	1.47×10^{-1}
19	1.47×10^{-1}
20	1.47×10^{-1}

In Table 2.6 the points 4 and 9, 5 and 8, 6 and 7, 20 and 19, 17 and 18, 16 and 13, 3 and 10 and 15 and 14 have the same value and the magnetic field is symmetric in the zone covered by these points, however the points 1 and 2 have a different magnitude value because in the tee's there is zones where the flux lines are more concentrated and the magnetic field in theses zones has a bigger value. This phenomenon is illustrated by the small circles in Figure 2.9.

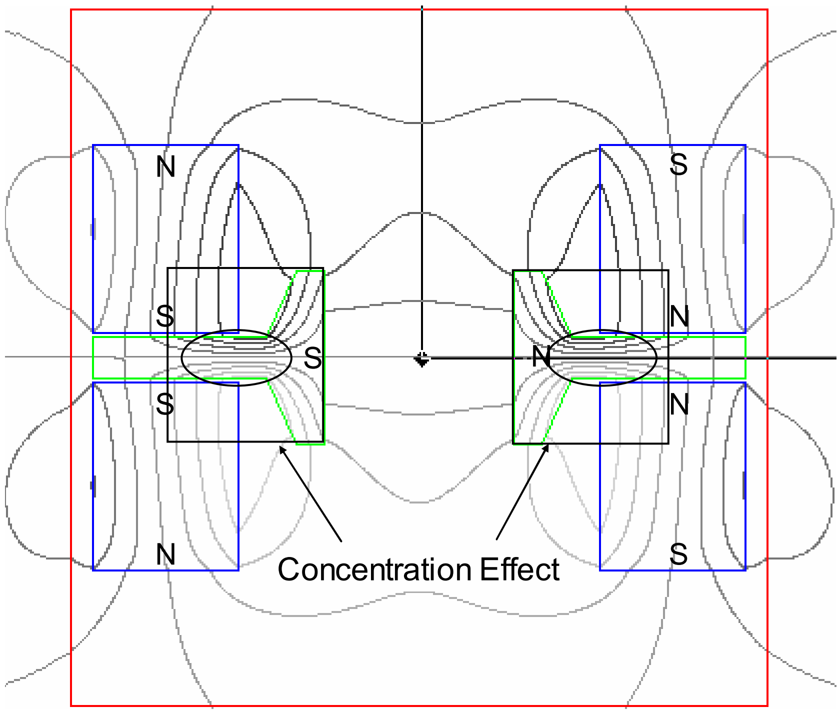


Figure 2.10. Concentration of flux lines in Configuration 3.

The tee on the right acts as "emitter" of magnetic field and the tee of the left acts as a "collector" of magnetic field.

The points 1, 2, 6, 20, 17 of Figure 2.9 are in the concentration zone and these are compared with their counterparts 12, 13, 7, 8, 9 of Figure 2.7 the comparison of the magnetic field for these points is given in Table 2.7. The points 1, 2, 3, 4, 5, 6, 20, 17, 16, 15 in Figure 2.9 are geometrically symmetric to the points 12, 13, 1, 5, 6, 7, 8, 9, 10, 11 in Figure 2.7 a comparison of the magnetic field for these points is given in Table 2.8.

Table 2.7. Concentration Effect. Configurations 3 and 2.

Figure 2.9 point	**Magnetic Field Magnitude (T)**	**Figure 2.7 point**	**Magnetic Field Magnitude (T)**	**Percent of increment**
1	1.02	12	9.5×10^{-1}	7.4
2	8.8×10^{-1}	13	8.3×10^{-1}	6
6	1.47×10^{-1}	7	1.2×10^{-1}	22.5
17	1.47×10^{-1}	9	1.2×10^{-1}	22.5
20	1.47×10^{-1}	8	1.2×10^{-1}	22.5

Table 2.8. Symmetric Points. Configurations 3 and 2.

Figure 2.9 point	**Magnetic Field Magnitude (T)**	**Figure 2.7 point**	**Magnetic Field Magnitude (T)**	**Percent of increment**
1	1.02	12	9.5×10^{-1}	7.4
2	8.8×10^{-1}	13	8.3×10^{-1}	6
3	1.47×10^{-1}	1	1.2×10^{-1}	22.5
4	5.8×10^{-11}	5	6.9×10^{-10}	-91.6
5	1.47×10^{-1}	6	1.2×10^{-1}	22.5
6	1.47×10^{-1}	7	1.2×10^{-1}	22.5
17	1.47×10^{-1}	9	1.2×10^{-1}	22.5
20	1.47×10^{-1}	8	1.2×10^{-1}	22.5

In Tables 2.7 and 2.8 the contribution to the magnetic field from the new tee and permanent magnets is revealed and the trend to concentrate the field to the center of the configuration is also confirmed. In a magnified view of the bending zones the change in the direction of the magnetic field can be better illustrated. The following Figure is a magnified view of Figure 2.10. The small circles indicate the zones where the total magnetic field is reduced because the opposite direction of magnetic field.

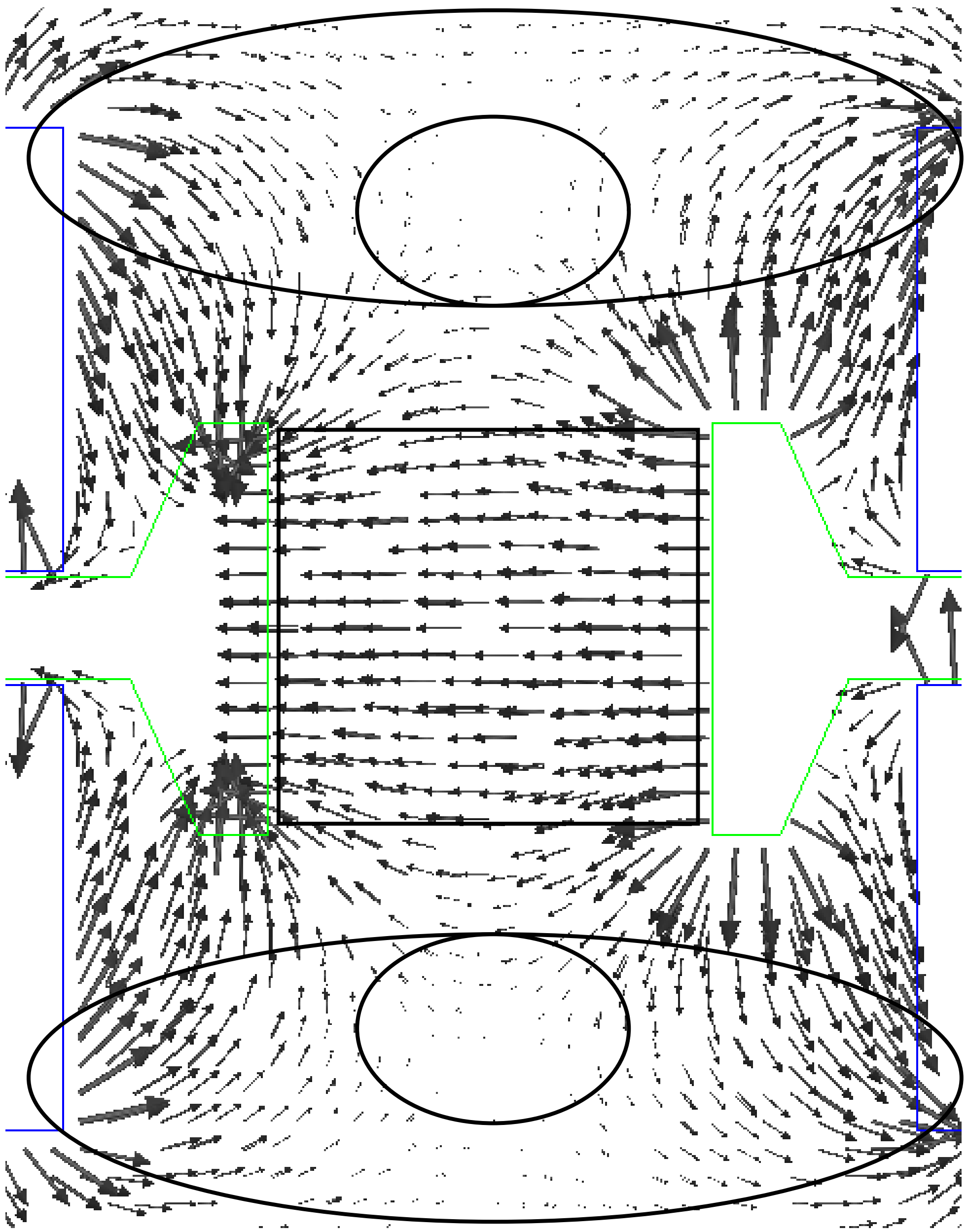


Figure 2.11. Bending and Uniform Zones for the Magnetic Field. Configuration 3.

In this Figure the area surrounded by the big circles are the bending zones that affect the force. Now the bending zones are bigger because every tee has its own bending zones. When the tee's are placed as in Configuration 3, the bending zones are expanded but due to the different poles associated with the tee's, in the center of the bending zones, the magnetic field of the left magnets presents an opposite direction to the one of the right magnet. This generates a dramatic reduction of the magnetic field in the bending zones and the force over the winding will be reduced when the winding or a part of it is immersed in the bending zones. The zones where the magnetic fields have opposite direction are demarcated by the small circles in Figure 2.11. The zone where the magnetic field has a uniform and well defined direction is also observed. This zone is demarcated by the rectangle in Figure 2.11. In case of dimension reduction of the tee faces the bending zones will be more accentuated and uniform zones will be reduced.

2.1.5. Configuration 4

The characteristics of Configuration 4 are listed in Figure 2.12. The separation between the tees and the permanent magnets is 0.001". The materials of the tee's and permanent magnets remain the same.

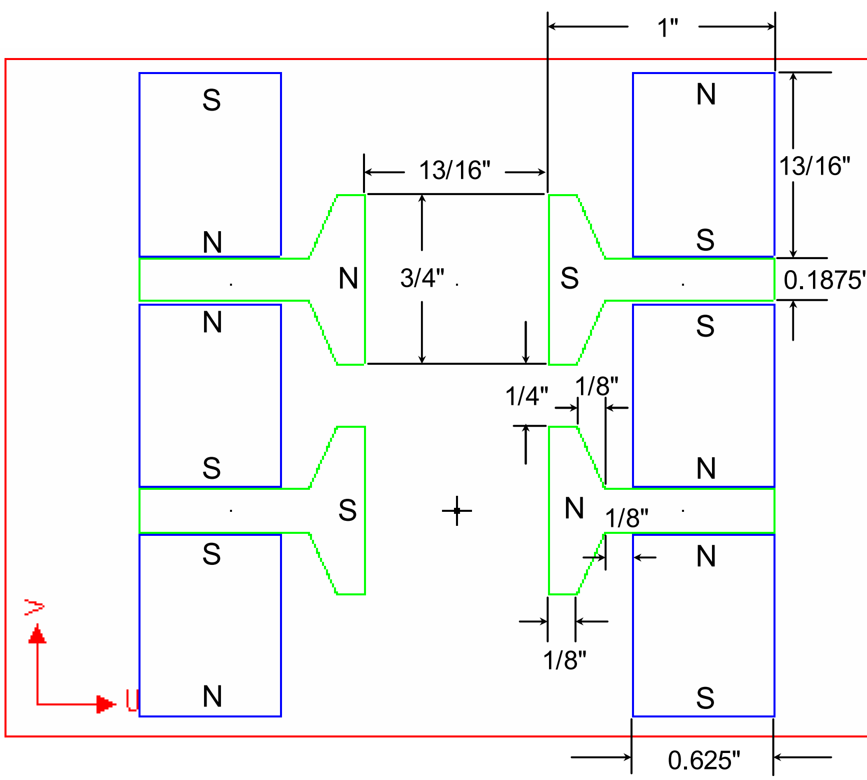


Figure 2.12. Configuration 4.

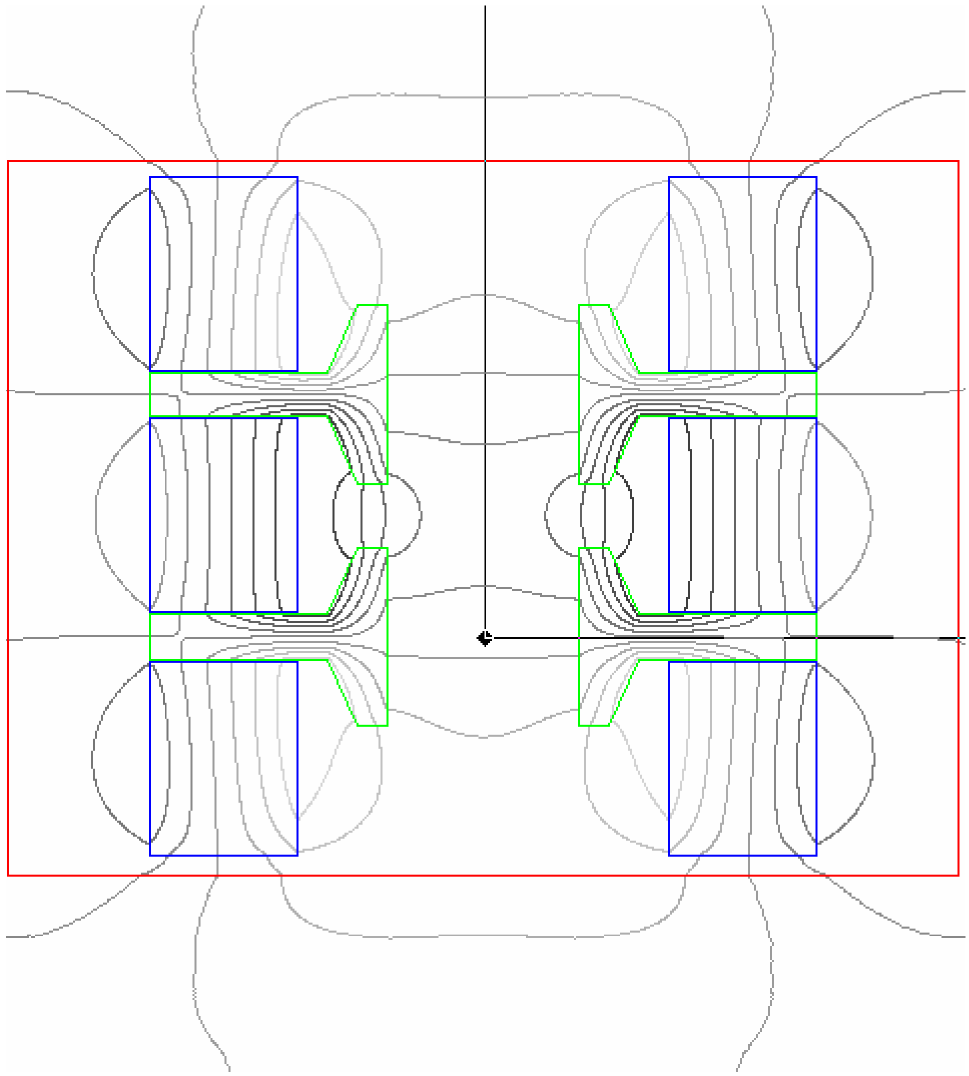


Figure 2.13. Flux Lines. Configuration 4.

In Figure 2.13 the flux lines are mainly concentrated in the center of the array, eliminating the magnetic field in both sides of the array. This is because the concentration effect. It is important to notice how the flux lines converge to the tee faces, where the magnetic field is bigger.

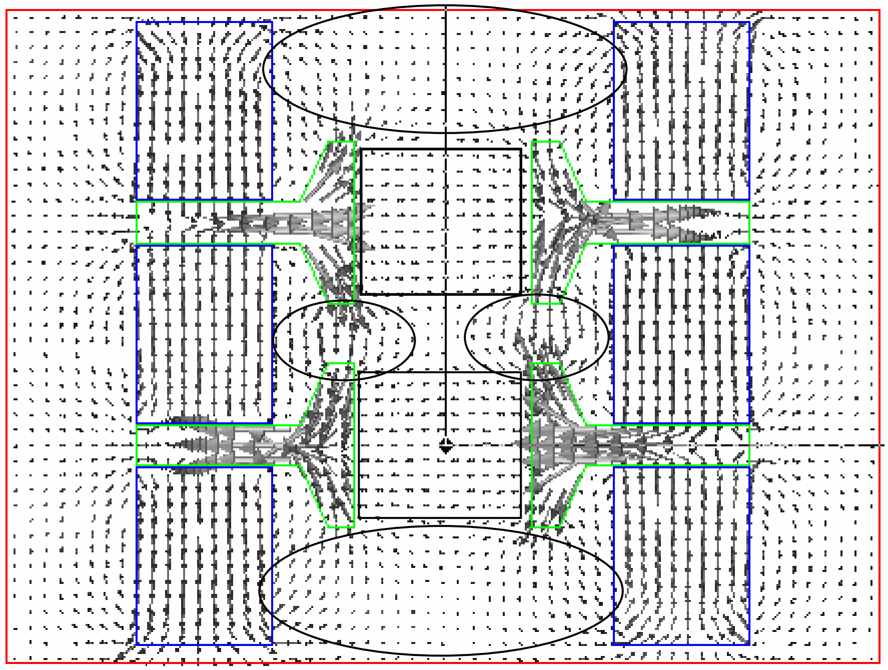


Figure 2.14. Magnetic Field. Configuration 4.

Figure 2.14 reveals some important characteristics of this configuration:

- The bending zones between the tee's are demarcated by the small circles and these are smaller than the bending zones demarcated by the big circles. The difference in size of these areas is because when the two extra tee's are added the region of air between the edges of the tee's is smaller. An increment of the magnetic field can be expected inside the small circles however in the region between the two circles the magnetic field still presents opposite directions and a dramatic reduction is also expected the zones are illustrated in Figure 2.15.

- The bending zones can be reduced by placing the tee's in the way illustrated by Figure 2.14. The magnetization direction of the permanent magnets also contributes to the reduction of the bending zones.

— The zones between the tee faces are zones of uniform direction of magnetic field. The size of these zones is directly related with the size of the tee faces as can be seen in the two rectangles of Figure 2.14. A more precise view of the small bending zones is shown in Figure 2.15.

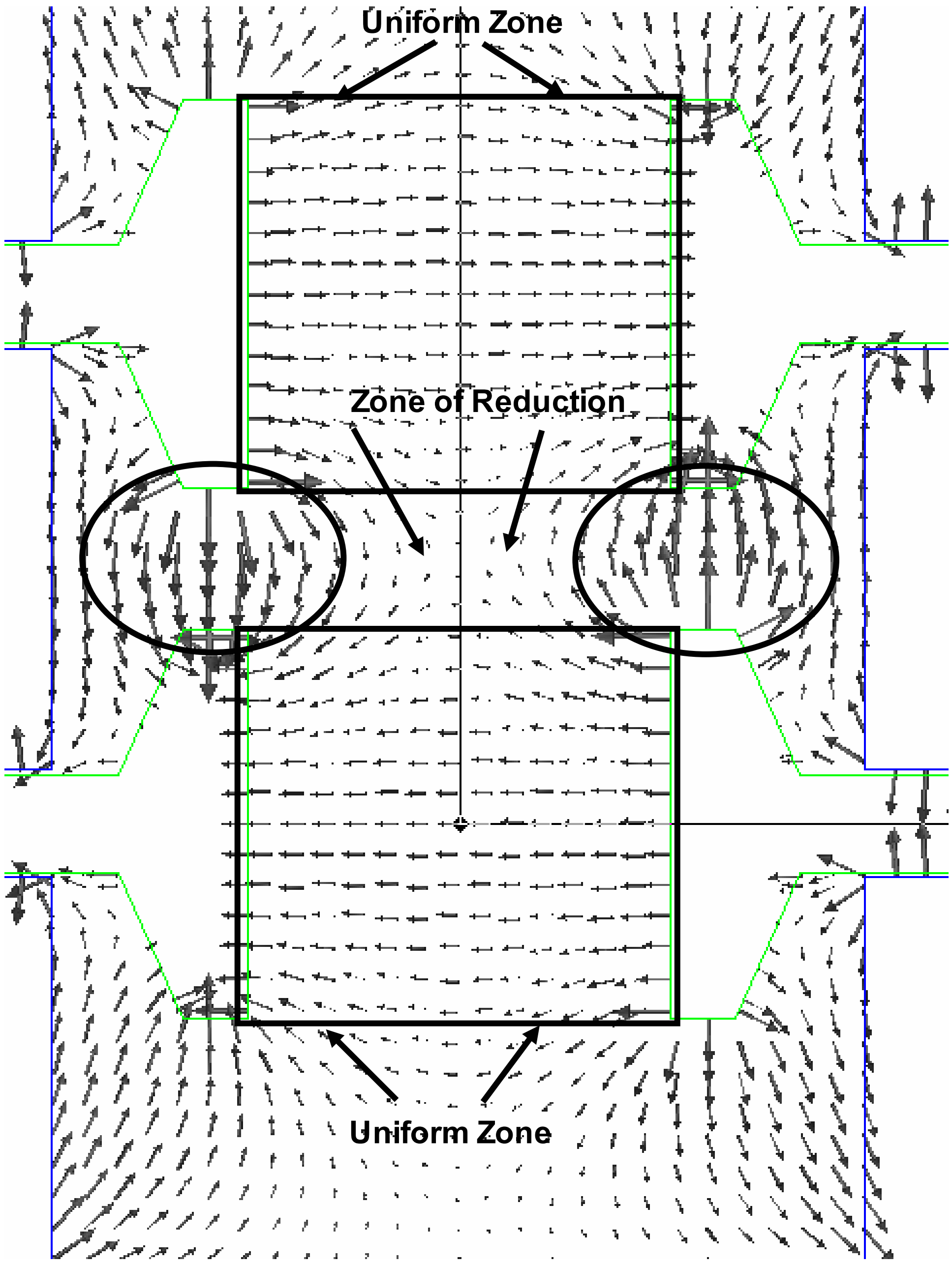


Figure 2.15. Magnified View of Bending Zones. Configuration 4.

In Figure 2.15 it is obvious the difference in size of the bending zones and how the direction of the magnetic field is changed in these zones. In this Figure the change in direction of the magnetic field in the uniform zones is also notorious.

In order to analyze the magnetic contribution of the two other tee's a measure of the magnitude of magnetic field has been done for several points illustrated in the following Figure. A comparison of the magnetic field in these points is shown in the next Table.

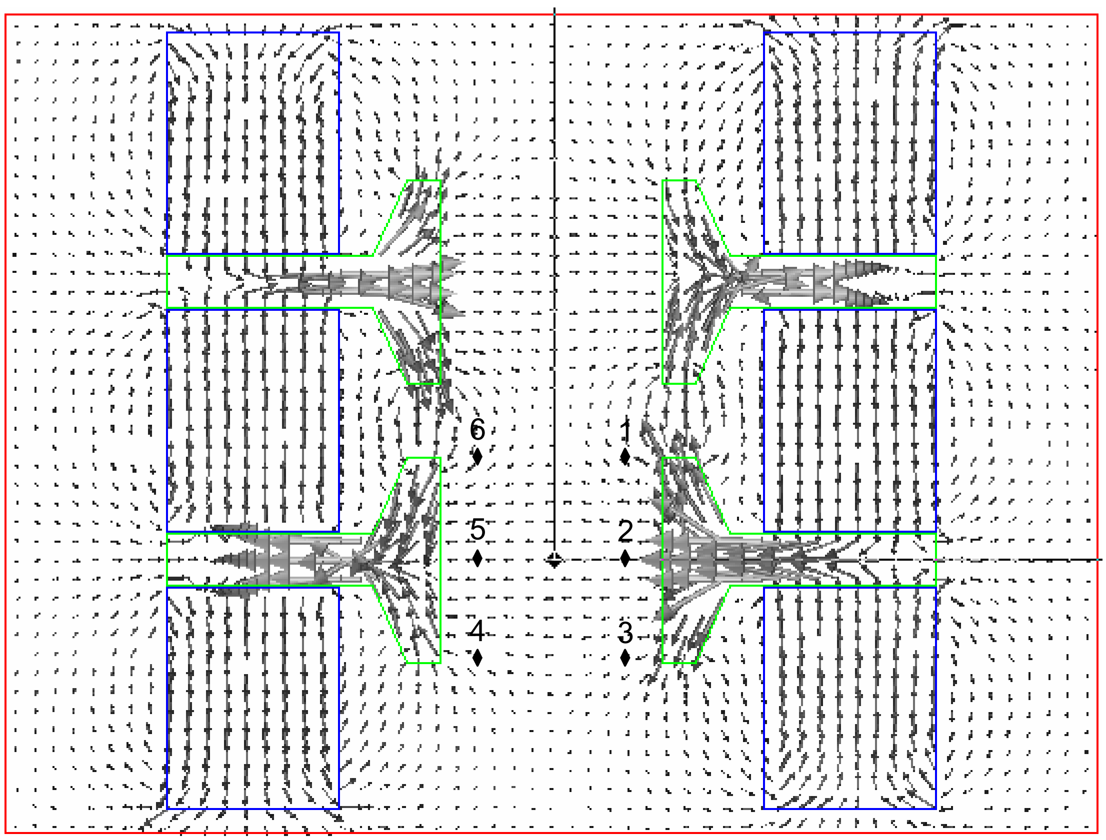


Figure 2.16. Measure Points of Magnetic Field. Configuration 4.

The points 1, 2, 3, 4, 5, 6 are in the same position of the points 6, 20, 17, 18, 19, 7 in Figure 2.9.

Table 2.9. Concentration Effect. Configurations 4 and 3.

Figure 2.16 point	**Magnetic Field Magnitude (T)**	**Figure 2.9 point**	**Magnetic Field Magnitude (T)**	**Percent of increment**
1	1.56×10^{-1}	6	1.47×10^{-1}	6.1
2	1.56×10^{-1}	20	1.47×10^{-1}	6.1
3	1.56×10^{-1}	17	1.47×10^{-1}	6.1
4	1.56×10^{-1}	18	1.47×10^{-1}	6.1
5	1.56×10^{-1}	19	1.47×10^{-1}	6.1
6	1.56×10^{-1}	7	1.47×10^{-1}	6.1

The values presented in Table 2.9 reveal that the contribution of the two extra tee's to the magnitude of the magnetic field is small just 6.1 %. The main contribution of the tees and permanent magnets lies in the reduction of the bending zones. This justifies the addition of more tee's and permanent magnets. Taking advantage of the reduction in bending zones two extra tee's and permanent magnets are added to Configuration 4 as illustrated in Figure 2.17. This configuration will be named Configuration 5. The dimensions of tee and permanent magnet remain the same.

2.1.6. Configurations 5 and 6.

In Configuration 5 a pattern is confirmed:

- Reduction of the size of bending zones by placing tee's and permanent magnet with the appropriate magnetization direction.

- Concentration of the flux lines is mainly in the neck of the tee's and it is in this zone of the tee where the magnetic field is stronger.

- Reorientation of the magnetic field to the center of the configuration and elimination of it in both sides of the array.

— In the tee's a virtual magnetic pole is created depending on the magnetization direction of the permanent magnets.

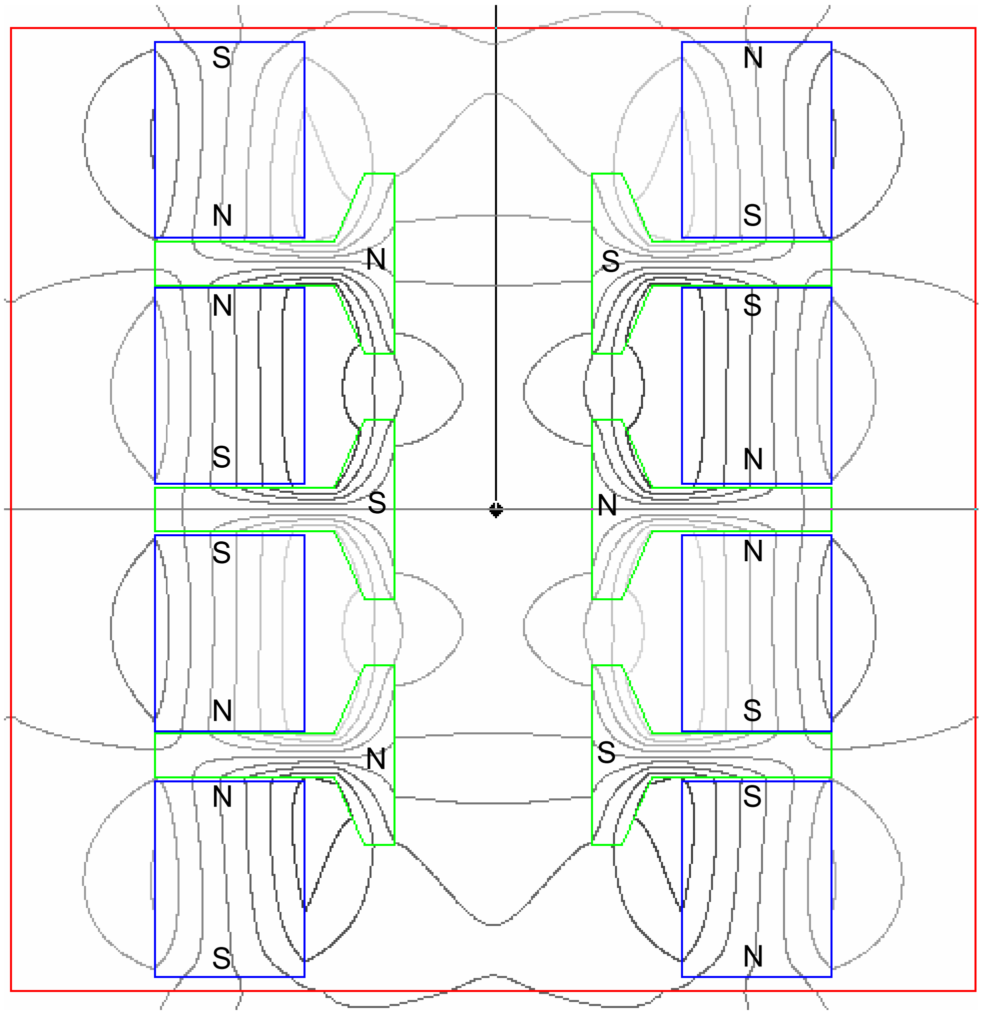


Figure 2.17. Flux Lines. Configuration 5.

In next Figure the magnetic field and some points where the magnetic field is measured are shown. The points in Figure 2.18 are in the same position of the points in Figure 2.16. In Table 2.10 a comparison of the magnetic field is done.

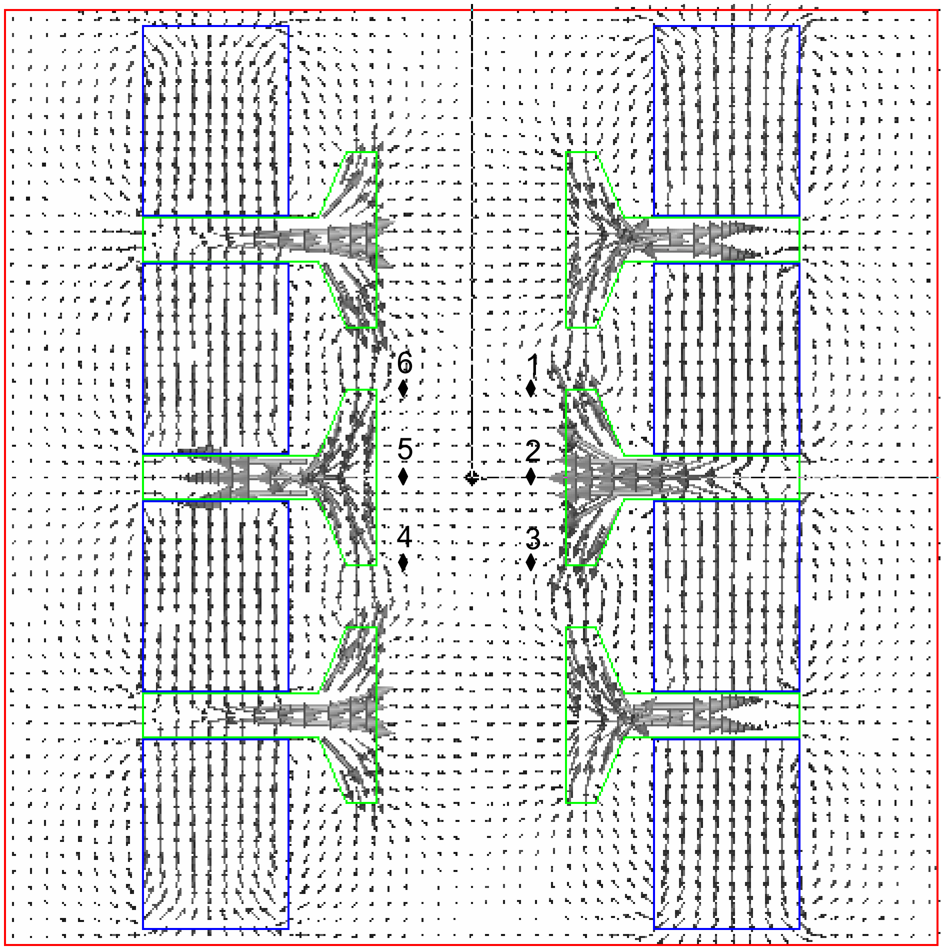


Figure 2.18. Magnetic Field. Configuration 5.

Table 2.10. Concentration Effect. Configurations 5 and 4.

Figure 2.18 point	Magnetic Field Magnitude (T)	Figure 2.16 point	Magnetic Field Magnitude (T)	Percent of increment
1	1.63×10^{-1}	1	1.56×10^{-1}	4.5
2	1.63×10^{-1}	2	1.56×10^{-1}	4.5
3	1.63×10^{-1}	3	1.56×10^{-1}	4.5
4	1.63×10^{-1}	4	1.56×10^{-1}	4.5
5	1.63×10^{-1}	5	1.56×10^{-1}	4.5
6	1.63×10^{-1}	6	1.56×10^{-1}	4.5

Again the contribution of the two new tee's to magnetic field is still small however its important role is represented by the reduction of the bending zones, concentration of the magnetic field and redirection of it creating the uniform zones with the same size of the tee faces. In the next Figure an extra pair of tee's is added and the consequences of this is analyzed in Figure 2.20. The contribution of the 4 new tee's is exposed in Table 2.11. The configuration will be named Configuration 6.

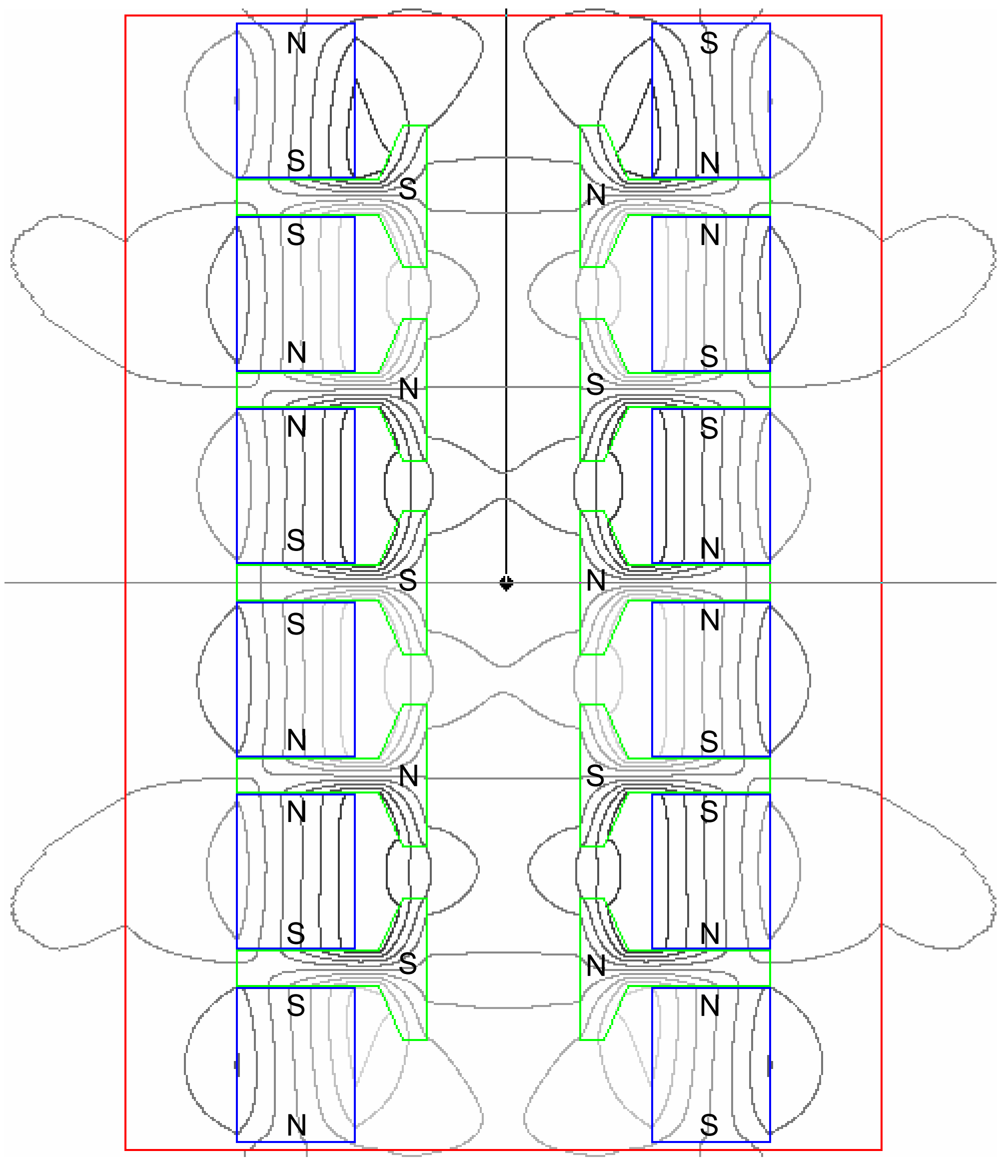


Figure 2.19. Flux Lines. Configuration 6

In Figure 2.19 it is confirmed how the configuration follows the pattern before mentioned.

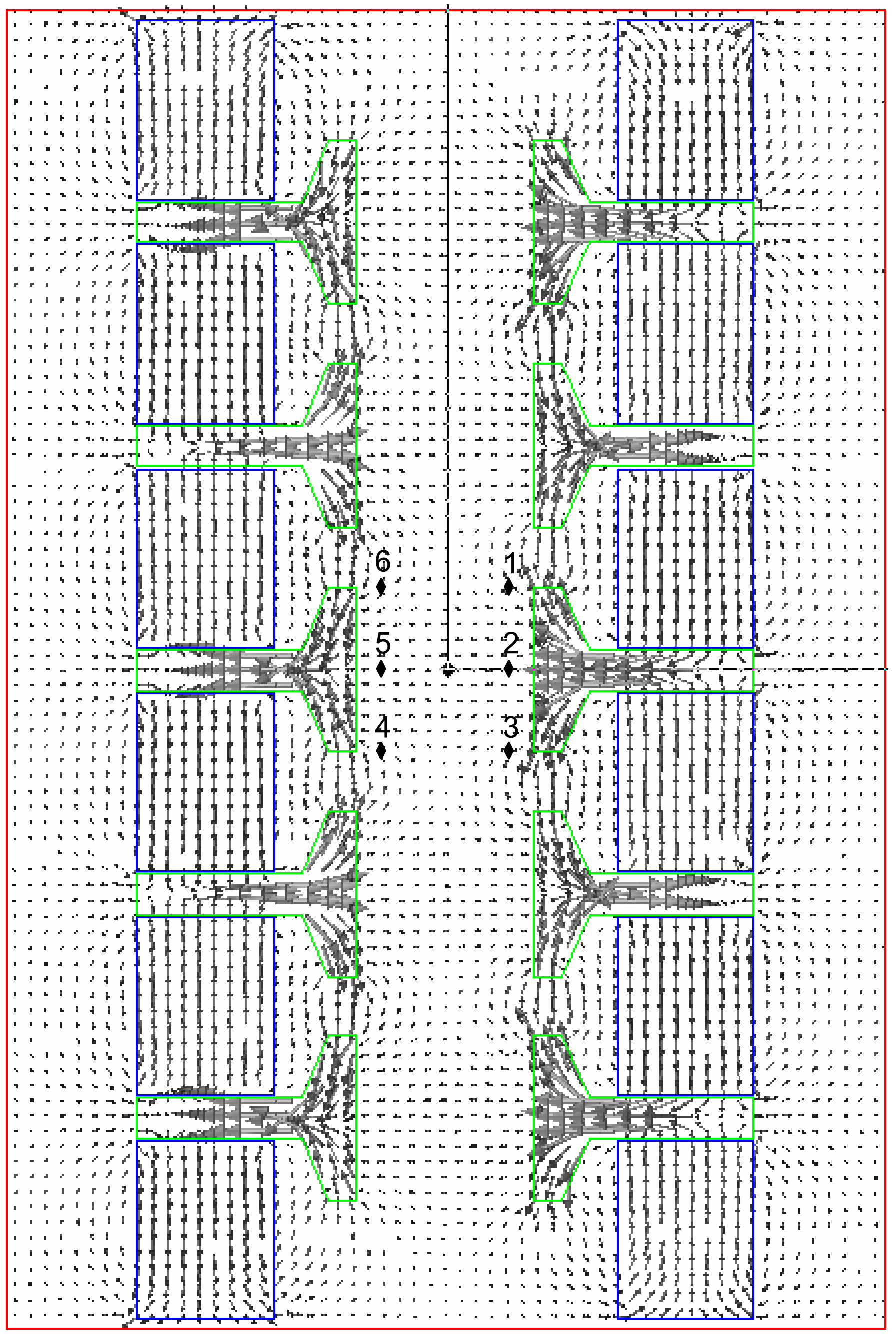


Figure 2.20. Magnetic Field. Configuration 6.

Table 2.11. Concentration Effect. Configurations 6 and 5.

Figure 2.20 point	Magnetic Field Magnitude (T)	Figure 2.18 point	Magnetic Field Magnitude (T)	Percent of increment
1	1.76×10^{-1}	1	1.63×10^{-1}	7.9
2	1.76×10^{-1}	2	1.63×10^{-1}	7.9
3	1.76×10^{-1}	3	1.63×10^{-1}	7.9
4	1.76×10^{-1}	4	1.63×10^{-1}	7.9
5	1.76×10^{-1}	5	1.63×10^{-1}	7.9
6	1.76×10^{-1}	6	1.63×10^{-1}	7.9

In Table 2.11 is confirmed that the contribution of the tee to the magnetic field is small but continuous. The reduction of the bending zones and concentration of the magnetic field is the important factor in the configurations.

The addition of tee's always represent reduction of bending zones, concentration of the field toward the center of the array and creation of uniform direction zones between the tee faces with the same size of them and these characteristics are very important. Until now the addition of pairs of tee's has been simulated and their effects were analyzed. Now a final configuration will be adopted in order to analyze the direction and magnitude of the force exerted by this configuration over a winding structure after the interaction between the magnetic field of the configuration and the magnetic field generated by the winding itself. This force will bring movement to the winding and therefore to the train, the control over this force will result in the control of velocity of the train.

2.1.7. Final Configuration

The characteristics of the final configuration are described in the next Figure. The dimensions of the tee's and permanent magnets remain the same. The separation between the tee's and permanent magnets is 0.001 (0254 mm)"

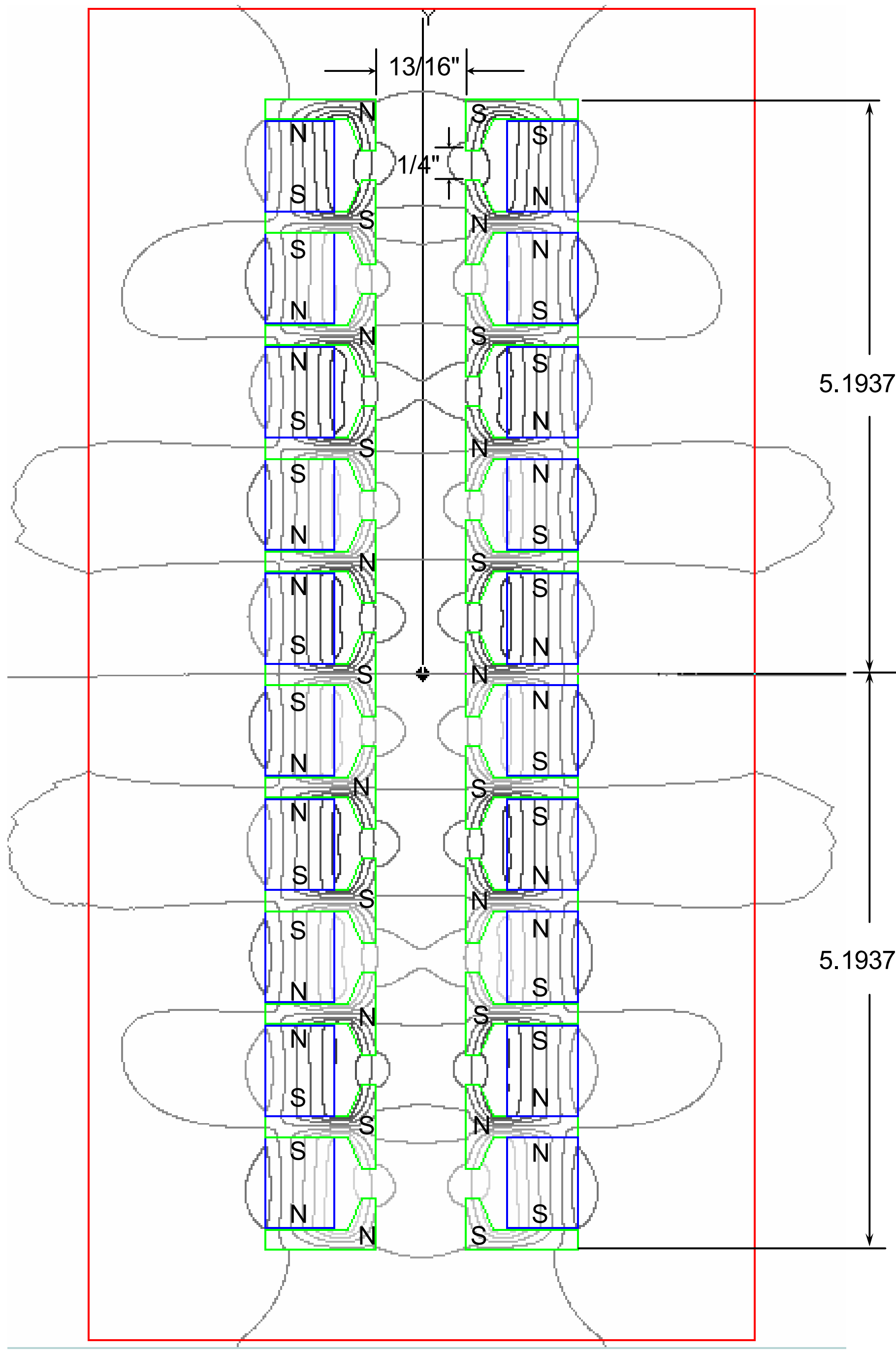


Figure 2.21. Flux Lines. Final Configuration

The number of tee's or permanent magnets doesn't matter because the concentration effect and the elimination of the field in both sides always take place.

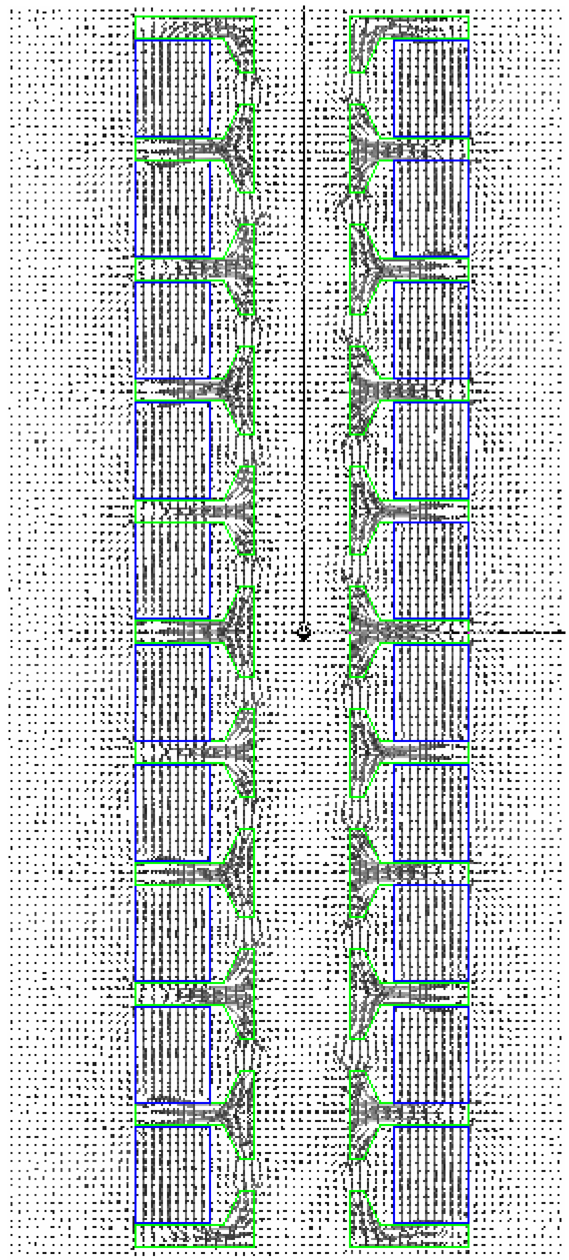


Figure 2.22. Magnetic Field. Final Configuration.

A magnified view of Figure 2.22 shows the points where the magnetic field was measured.

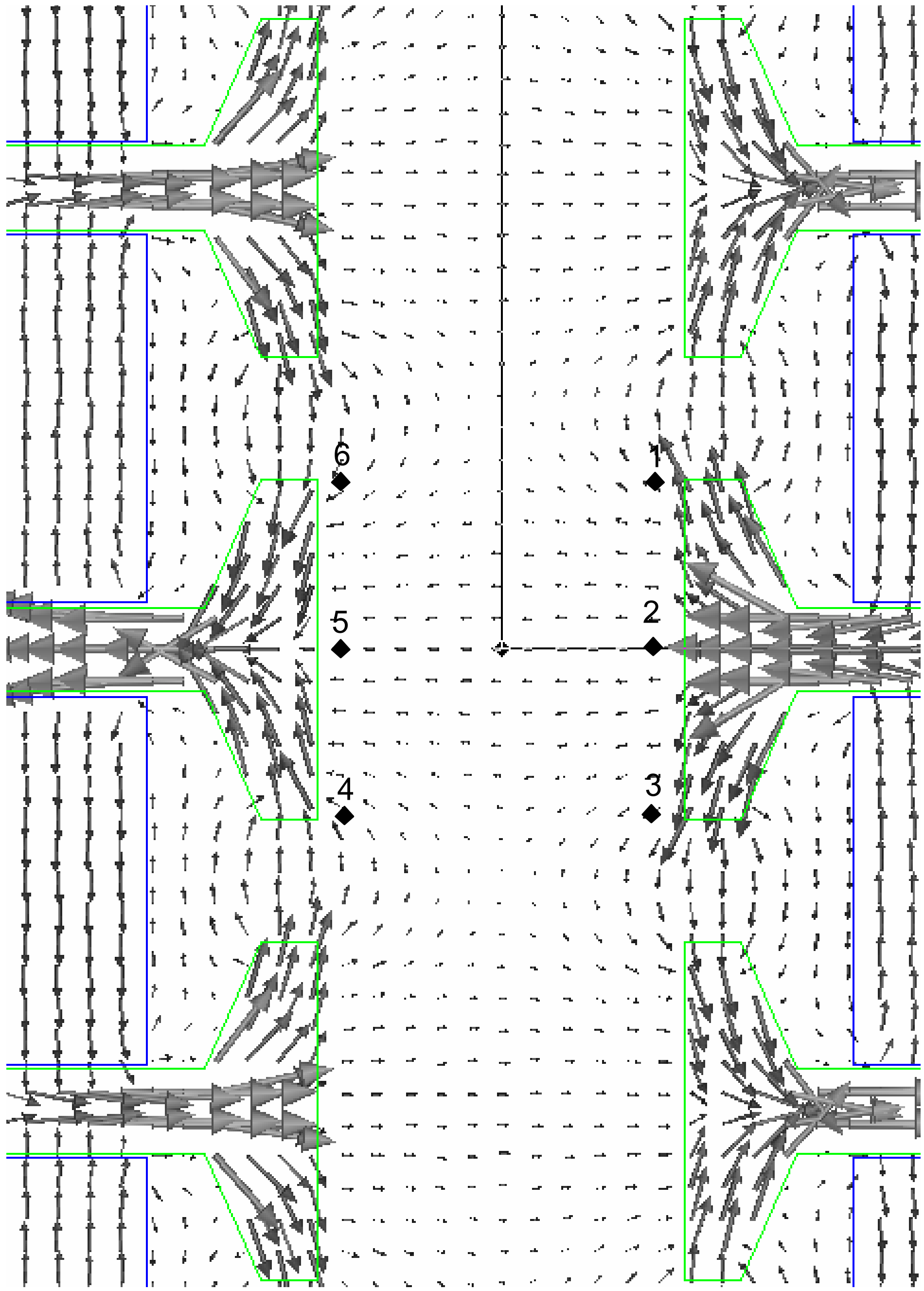


Figure 2.23. Magnified View of Final Configuration Magnetic Field.

The points 1, 2, 3, 4, 5 and 6 are in the same position of points 6, 20, 17, 18, 19 and 7 of Figure 2.9.

Table 2.12. Concentration Effect. Final Configuration and Configuration 6.

Figure 2.23 point	Magnetic Field Magnitude (T)	Figure 2.18 point	Magnetic Field Magnitude (T)	Percent of increment
1	1.89×10^{-1}	1	1.76×10^{-1}	7.4
2	1.89×10^{-1}	2	1.76×10^{-1}	7.4
3	1.89×10^{-1}	3	1.76×10^{-1}	7.4
4	1.89×10^{-1}	4	1.76×10^{-1}	7.4
5	1.89×10^{-1}	5	1.76×10^{-1}	7.4
6	1.89×10^{-1}	6	1.76×10^{-1}	7.4

As mentioned before the contribution of the tees to the magnetic field in the points of Figure 2.23 is small but it seams to increase up to about 7%. Figure 2.24 illustrates the increments of the magnetic field magnitude from Configuration 1 to final configuration

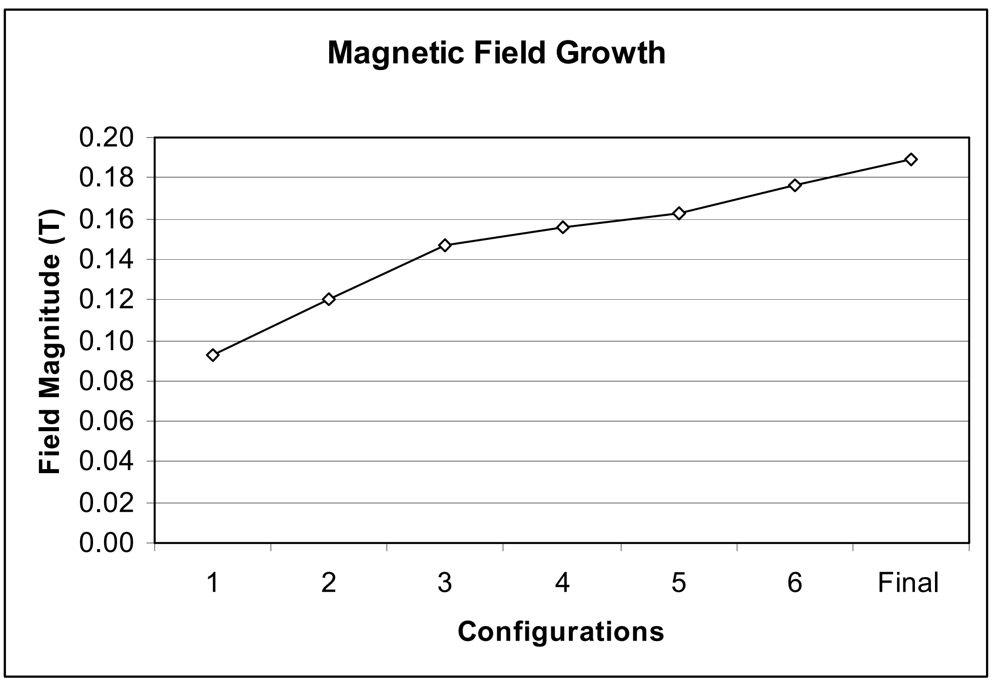


Figure 2.24. Magnetic Field Growth

2.1.8. Magnetic Field of Berdut Design and Halbach Array

As mentioned before the inductrack alternative uses only permanent magnets in a special array called Halbach array as a source of magnetic field. The Halbach array concentrates the magnetic field in one side of the array depending on the sense of the magnetization vector of the permanent magnets. The Berdut design concentrates the magnetic field in the center of the array. In this section a comparison of the magnetic field of both alternatives will be performed.

The Berdut design interlaces tee's between the permanent magnets. In these tee's and as a consequence of the ferromagnetic characteristics of the material a magnetic pole is created. This pole is directly related with the magnetization direction of the two permanent magnets at both sides of the tee's. To perform a comparison between these alternatives the dimensions of some permanent magnets of the Halbach arrays will be modified.

In Figure 2.25 the modifications and the magnetization direction are shown. The material of the permanent magnets of both alternatives is ceramic 5, the material of the tee's is cast iron.

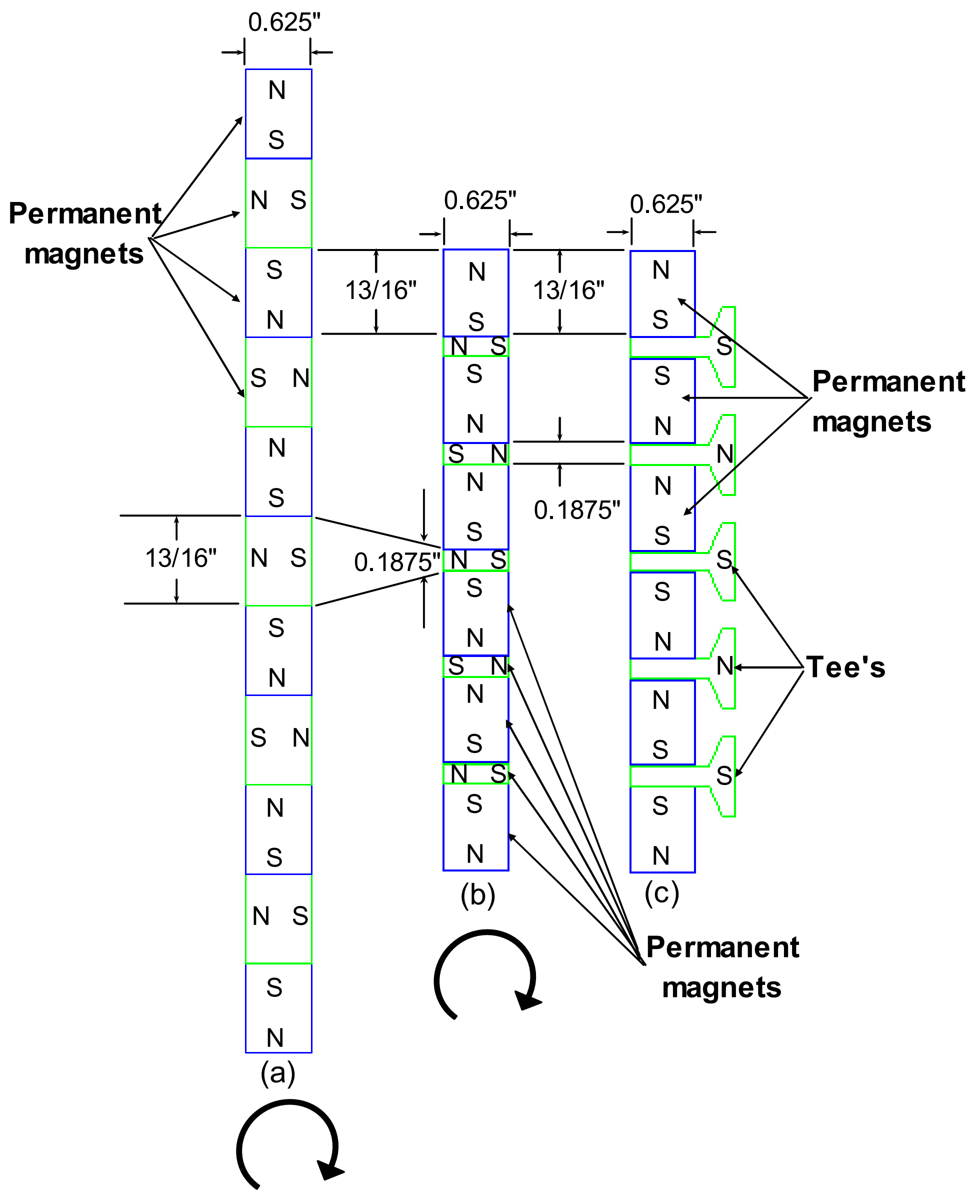


Figure 2.25. Modifications of Halbach Array. (a) Original Halbach Array, (b) Halbach Array Modified, (c) Berdut Design

In Figure 2.26 the simulation of the Halbach array modified and the part of Berdut design of Figure 2.25 are shown.

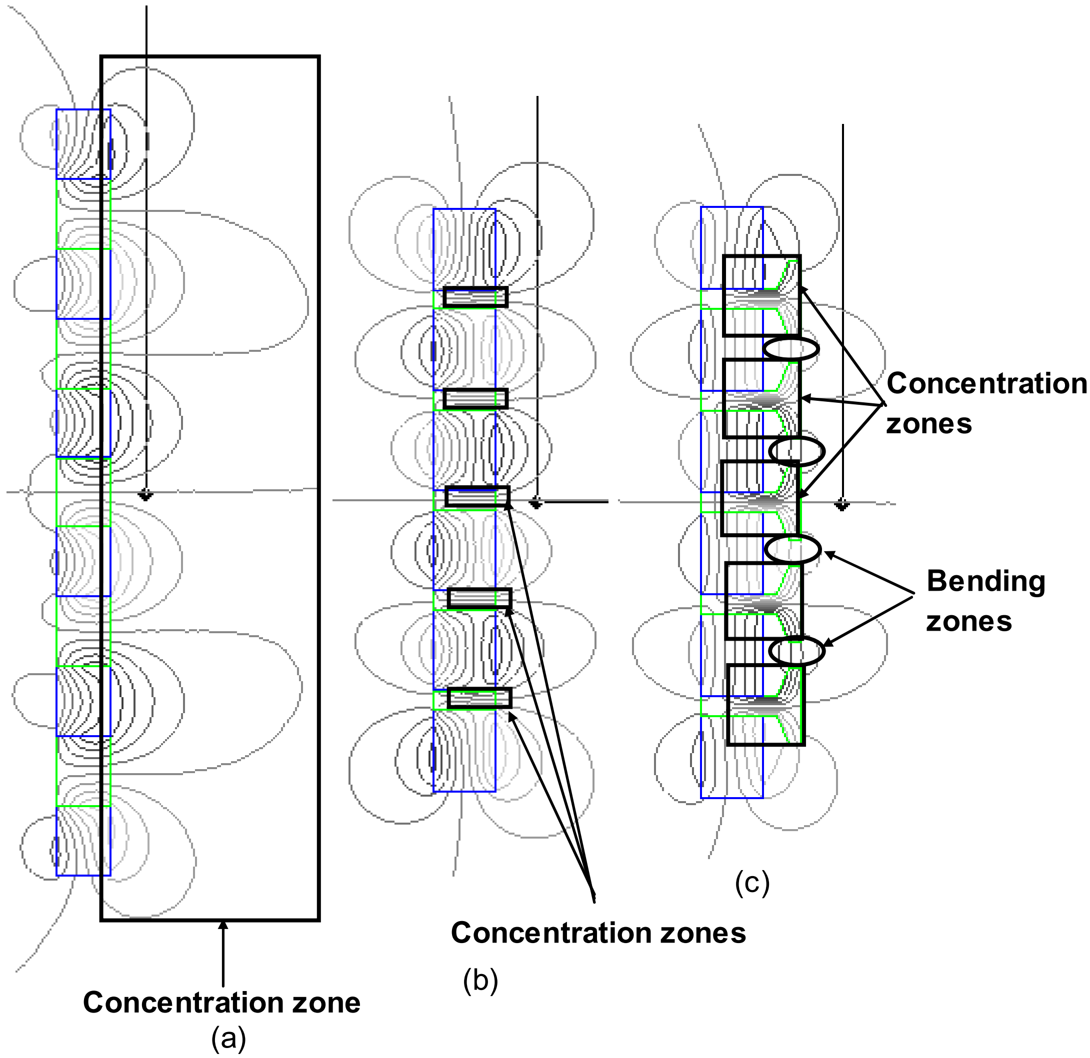


Figure 2.26. Flux Lines. (a) Original Halbach Array, (b) Halbach Array Modified, (c) Berdut Design

From Figure 2.26 a) and b) can be seen how the reduction of some permanent magnets of the Halbach array affects the concentration of the flux and therefore the magnetic field. In Figure 2.26 the concentration zones are demarcated by the rectangles and the bending zones are demarcated by the circles. From Figure 2.26 b) and c) can be seen how due to the tee face size the concentration zones in the berdut design are larger. In Figure 2.27 two Halbach arrays were placed like the Berdut design.

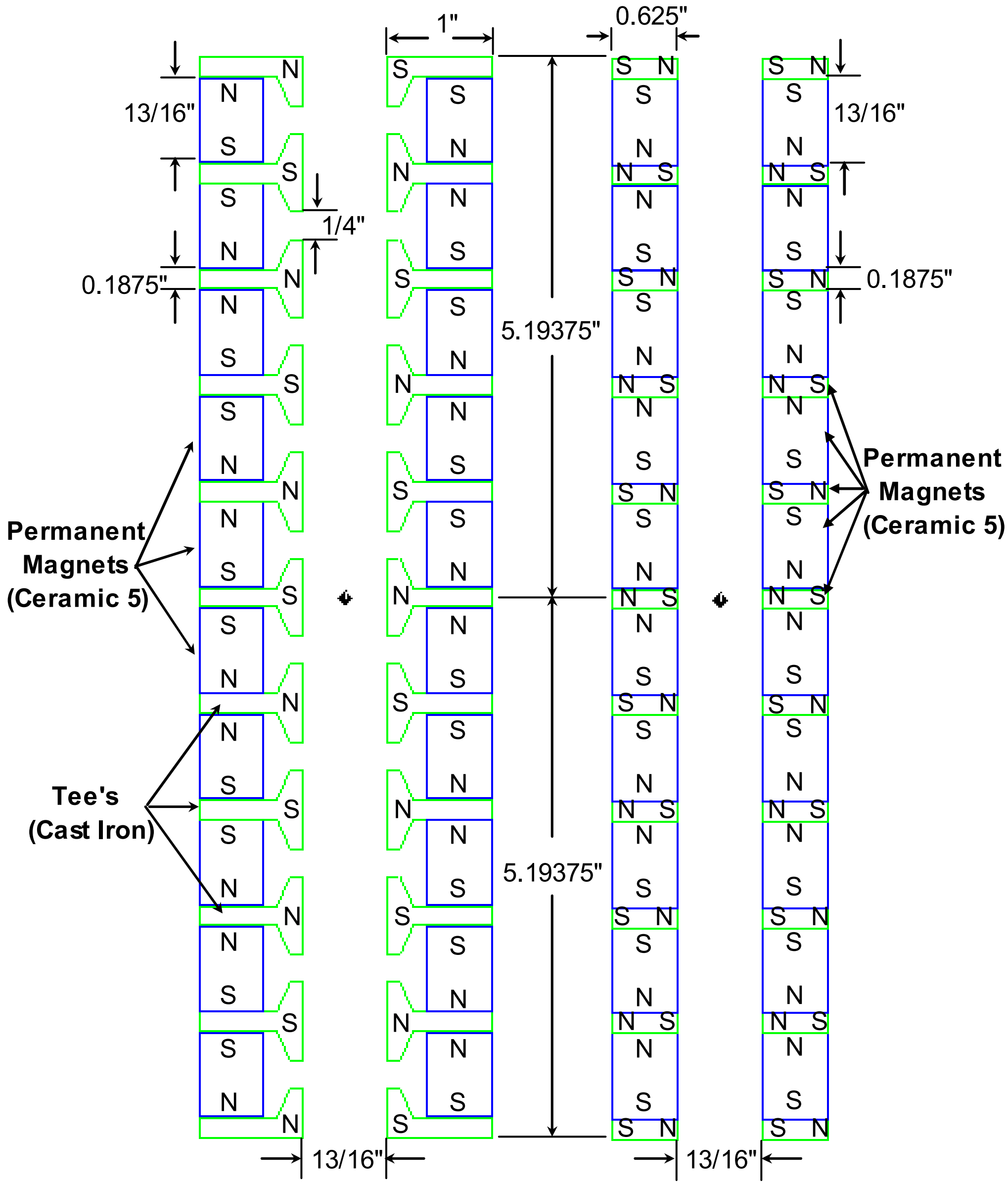


Figure 2.27. The Berdut Design and Modified Halbach Array

As can be seen in Figure 2.27 the dimensions of the Berdut design and the Halbach arrays are the same.

In the next Figure the flux lines of the Halbach arrays of Figure 2.27 are shown.

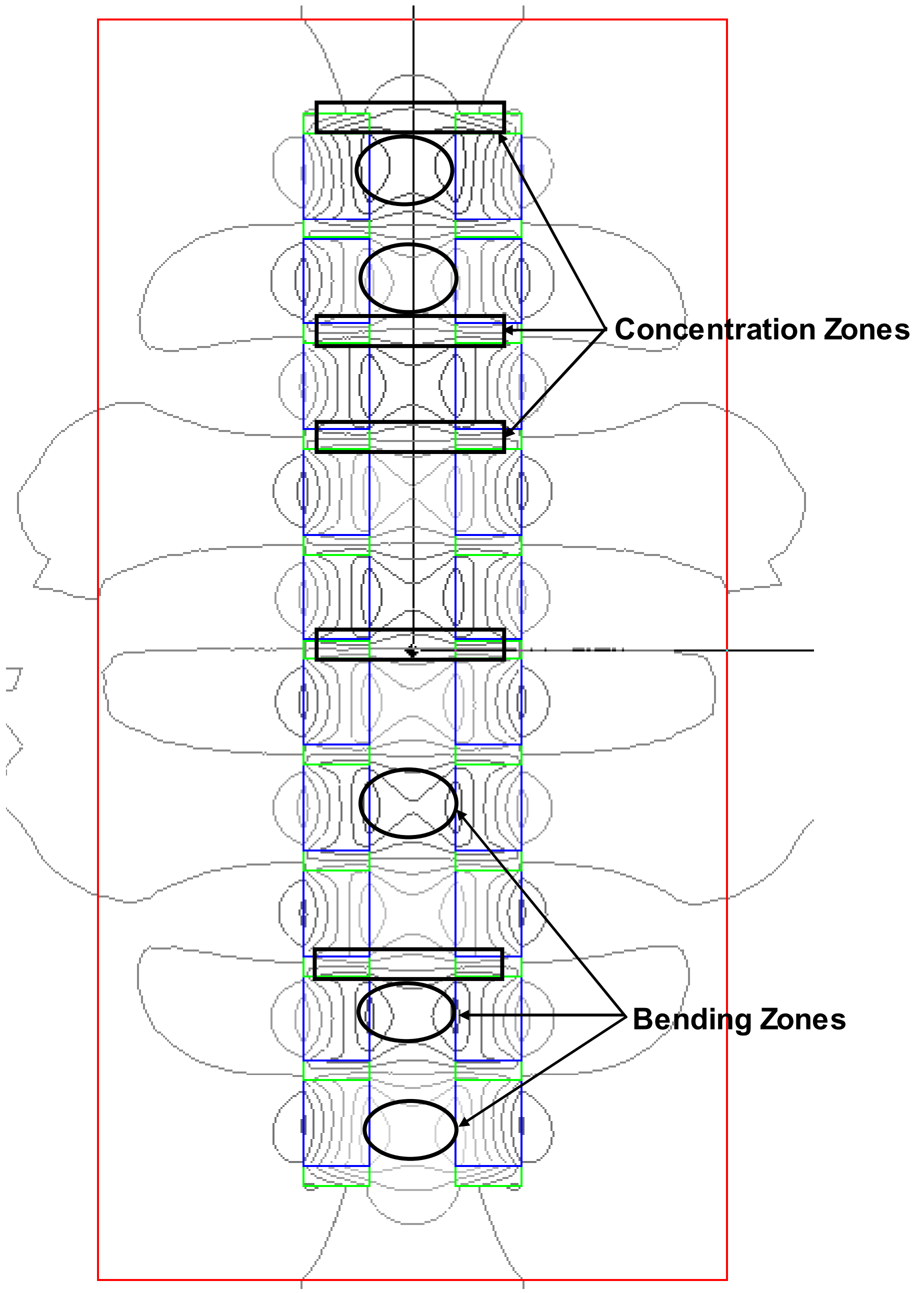


Figure 2.28. Flux Lines of the Modified Halbach Arrays placed like the Berdut Design

From Figure 2.28 the bending zones are bigger than the concentration zones due to the reduction of some permanent magnets in the Halbach array. In the concentration zones the direction of the magnetic field is uniform like in the Berdut design.

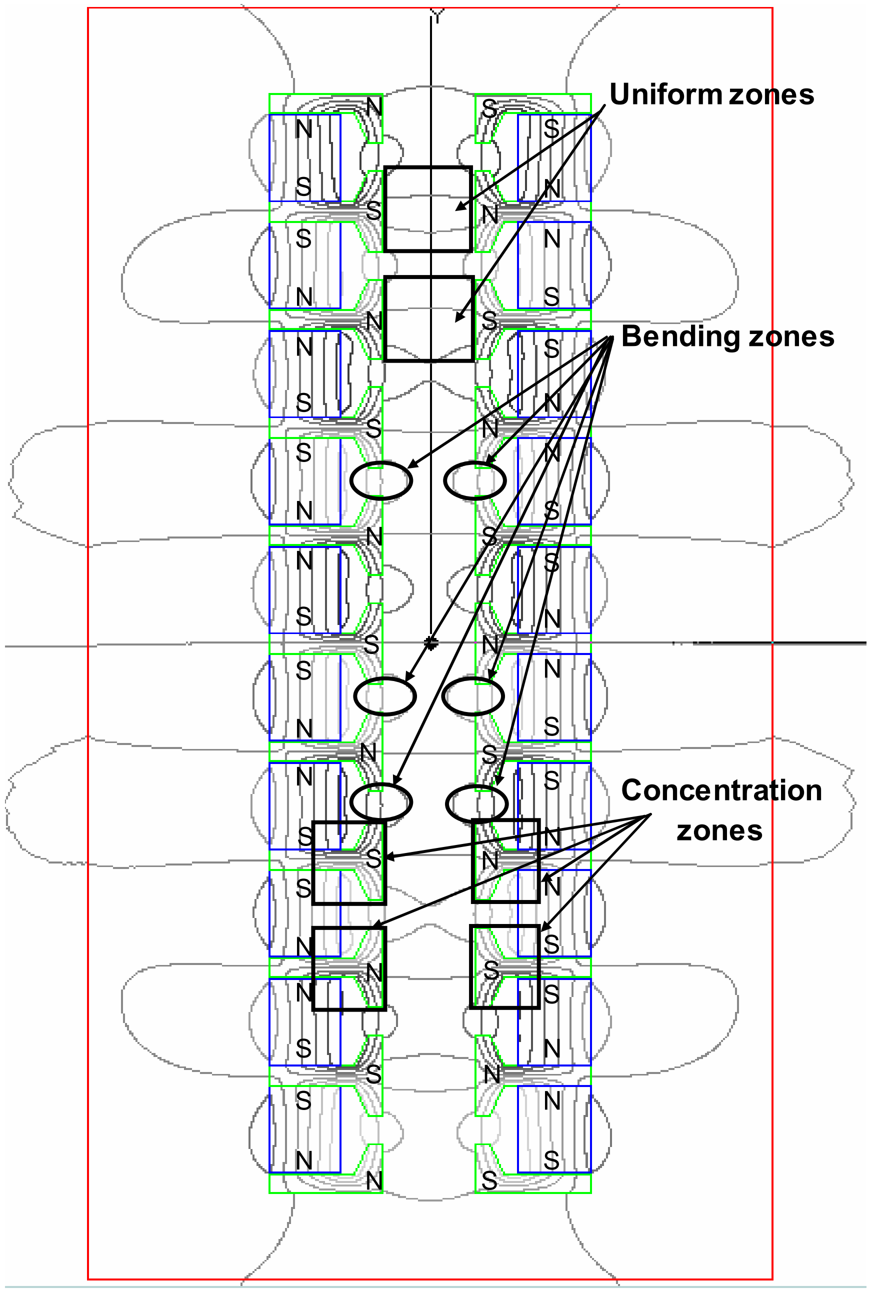


Figure 2.29. Flux Lines of the Berdut Design

From Figure 2.29 and Figure 2.28 the bending zones for the Berdut design are smaller than the bending zones for the Halbach arrays. The uniform zones of the Berdut design are bigger than the uniform zones of the Halbach arrays. However due to the better concentration of the flux lines in the smaller uniform zones of the

Halbach arrays the magnetic field magnitude is larger than the magnitude in the uniform zones of the Berdut design. As a consequence of smaller uniform zones the bending zones in the Halbach array are bigger. In the other hand the bending zones of the Berdut design are smaller presenting as consequence bigger uniform zones which is an advantage because in this zones the force direction will be well defined and the force magnitude is larger than the force created in the bending zones.

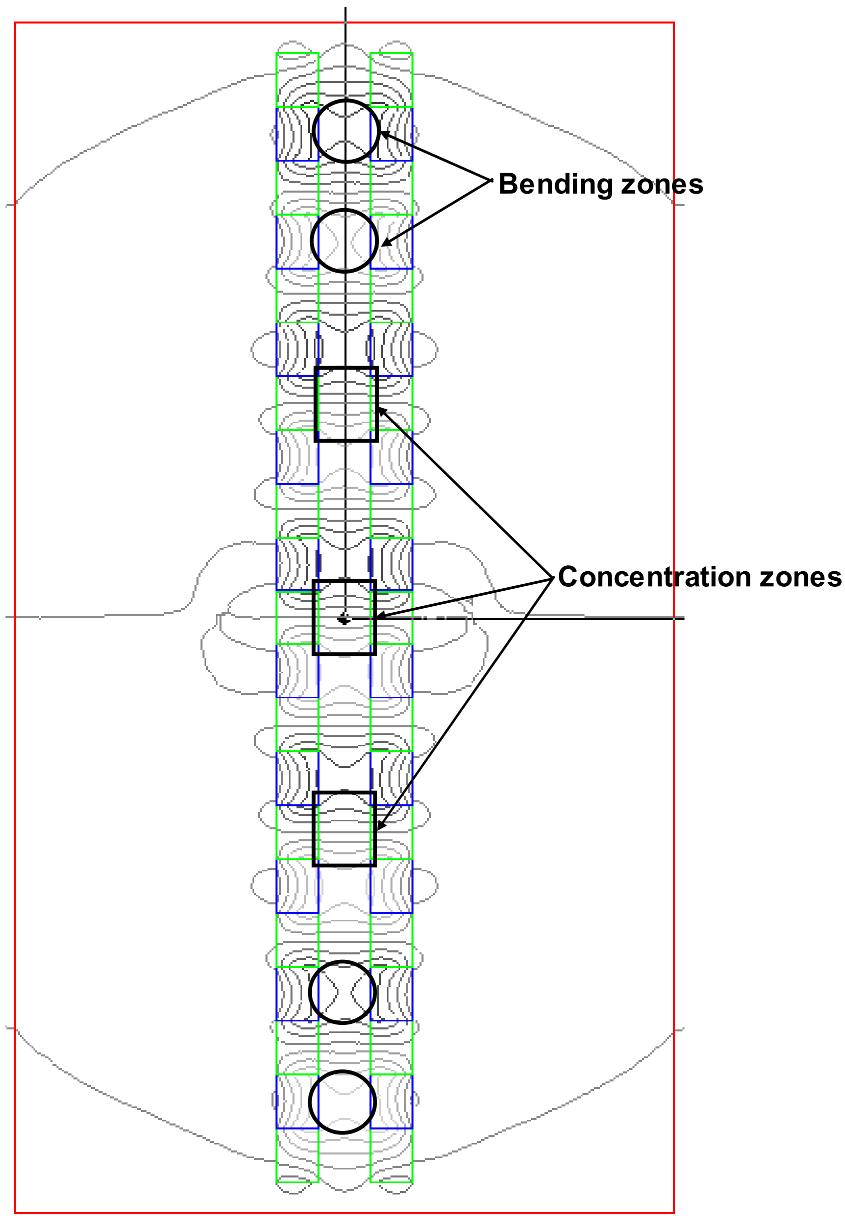


Figure 2.30. Flux Lines of the Original Halbach Arrays placed like the Berdut Design

In Figure 2.30 the flux lines of the two Halbach array without modifications are shown. Due to the same dimensions of the permanent magnets the uniform and bending zones for this configuration are almost equal in size. The better concentration of the flux lines in the uniform zones in Figure 2.30 has as consequence a larger magnetic field magnitude. In order to compare the magnetic field magnitude of the configurations of Figures 2.28, 2.29 and 2.30 some points where the magnetic field was calculated are presented in the next Figures. The points 1, 2, 3, 4, 5, and 6 of the next Figures are in the same position of the points 6, 20, 17, 18, 19, 7 of Figure 2.9.

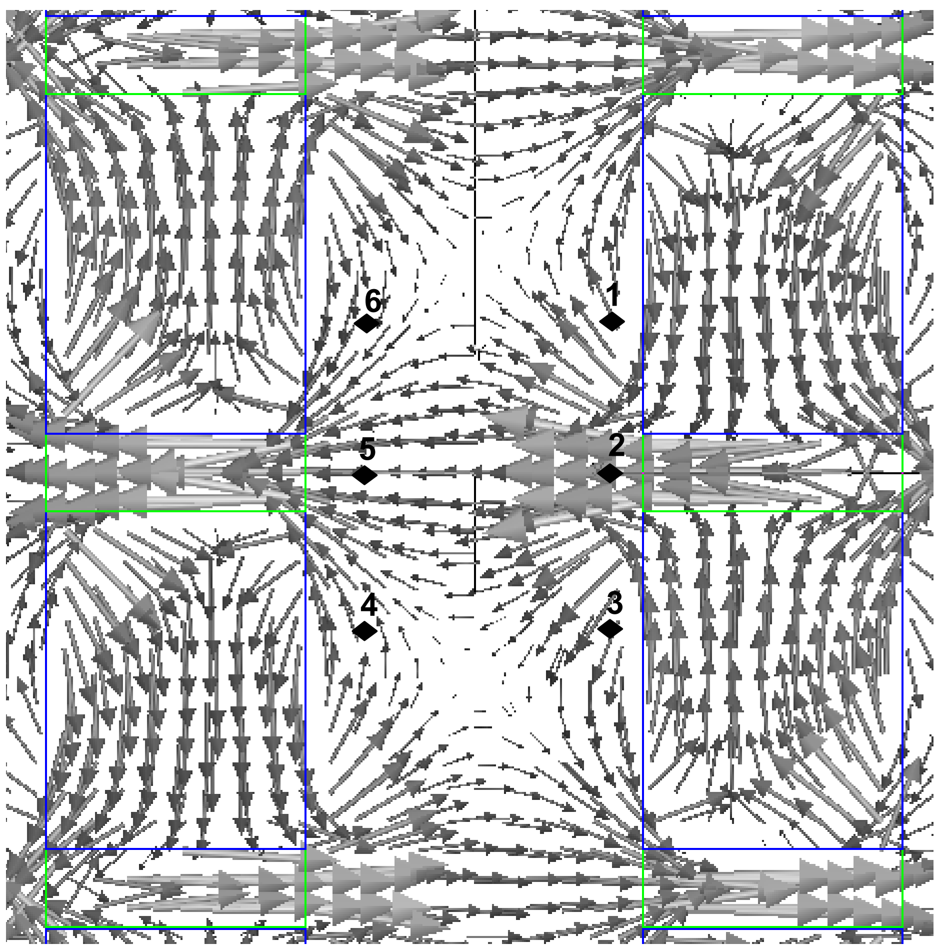


Figure 2.31. Magnetic Field. Halbach Arrays of Figure 2.28

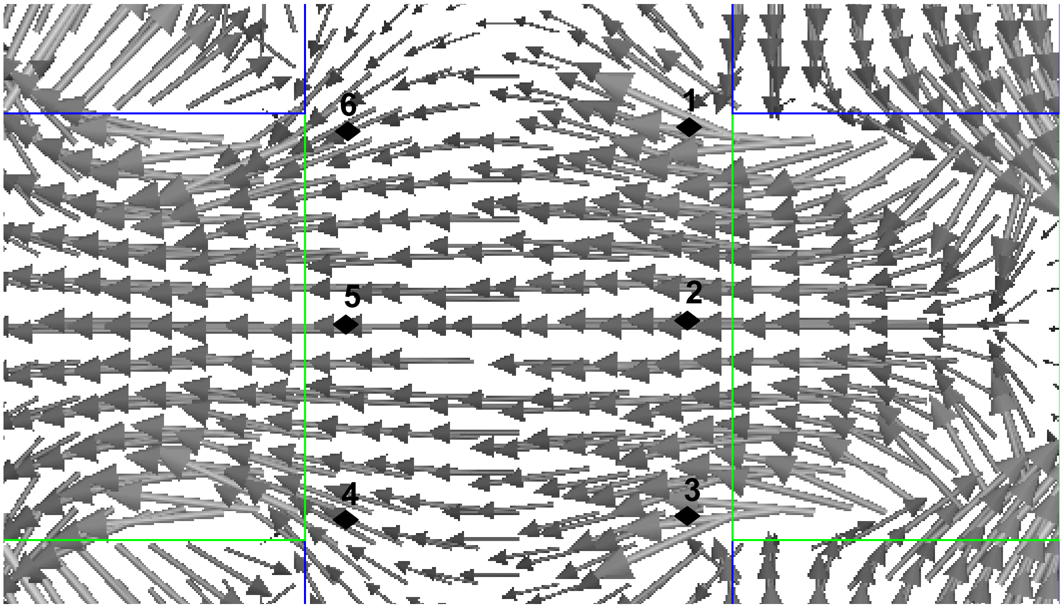


Figure 2.32. Magnetic Field. Halbach Arrays of Figure 2.30

Table 2.13 Magnetic Field Comparison Figures 2.23, 2.31 and 2.32

point	Magnetic Field Magnitude (T) Figure 2.23	Magnetic Field Magnitude (T) Figure 2.31	Magnetic Field Magnitude (T) Figure 2.32
1	1.89×10^{-1}	2.02×10^{-1}	2.776×10^{-1}
2	1.89×10^{-1}	3.54×10^{-1}	2.776×10^{-1}
3	1.89×10^{-1}	2.02×10^{-1}	2.776×10^{-1}
4	1.89×10^{-1}	2.02×10^{-1}	2.776×10^{-1}
5	1.89×10^{-1}	3.54×10^{-1}	2.776×10^{-1}
6	1.89×10^{-1}	2.02×10^{-1}	2.776×10^{-1}

Regarding Figure 2.31 the points 2 and 5 have the largest magnetic field in the table 2.13 because they are in the concentration zone and the concentration zones (see Figure 2.28) are the smallest and therefore the flux lines concentration is the best. Regarding the points in Figures 2.23 and 2.32 due to the better concentration of flux lines (see Figure 2.30) of the Halbach arrays the magnetic field magnitude of points in Figure 2.32 is larger than magnitude of points in Figure 2.23.

2.1.9. The Winding

The winding an important part of the configuration has not been analyzed. This part is responsible of the propulsion as well as the change in direction, and brake system simultaneously. With the objective of understanding the winding, its dimensions and magnetic behavior are presented. Due to limitations of the simulation software the winding will be represented as solid bars of copper with the exact dimensions of the Berdut windings. The characteristic for the simulation winding are explained in the next Figure. The calculation of the current flowing in the winding will be done using an AWG standard of 16 for the wire used in the future construction of the windings. In order to calculate the magnitude of the current is necessary calculate the area of the solid copper used in the simulations.

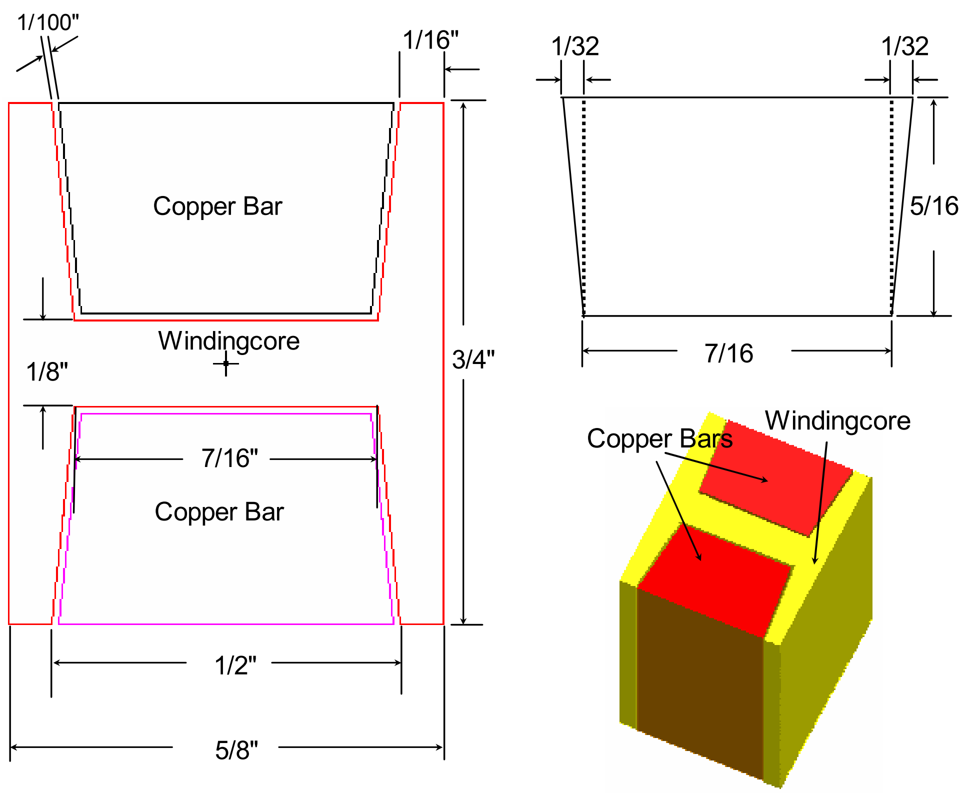


Figure 2.33. Winding. Parts and Dimensions.

Using Figure 2.33 the area of the copper bars is:

$$Total\ Area = \text{Re}\,c\tan gle\ \ Area + Traingles\ \ Area$$

$$Total\ Area = \frac{7}{16}\ x\ \frac{5}{16} + 2\ x\ \frac{1}{2}\ x\ \frac{1}{32}\ x\ \frac{5}{16} = 0.146\ in^2\ = 94.19\ mm^2$$

The numbers of turns will be:

$$Turns = \frac{Total\ Area}{Wire\ Area} = \frac{94.19}{1.31} \approx 72\ turns$$

This is just an approximation in the real number of turns because the wire is circular. Adopting a stack factor of 0.75 (the typical) the number of turns will be 54. Assuming 7 Amp per turn the total current will be 380 A-turn.

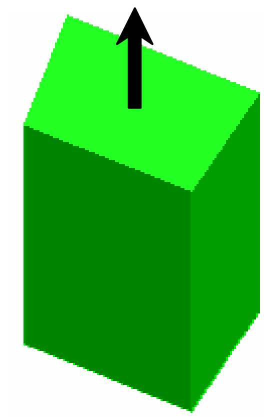
2.1.9.1. Magnetic Field Generated by the Copper Bars

The copper bars represent the winding but each copper bar can be seen as a solid conductor in which an electric current flows. The magnetic field generated in a wire is well known and its magnitude is stronger near the wire, the direction can be determined by the right hand rule for wires:

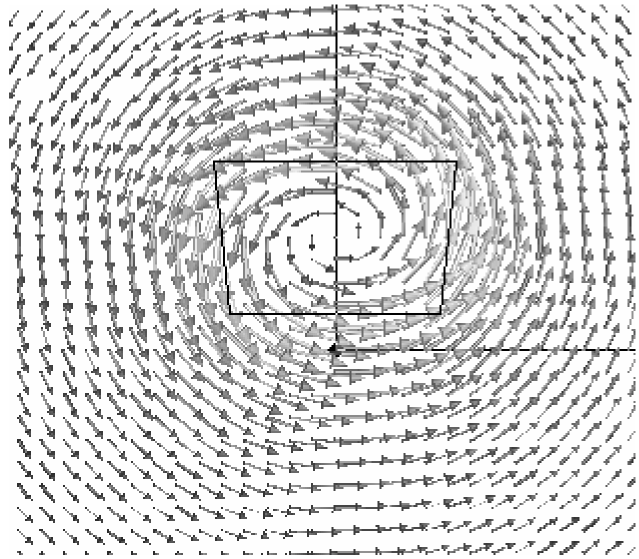
— The right thumb points in the same direction of the current.

— The direction of the magnetic field is the direction in which the fingers curl;

The simulation for each copper bar is listed in the next Figures. The current flowing in the copper bar was 380A.

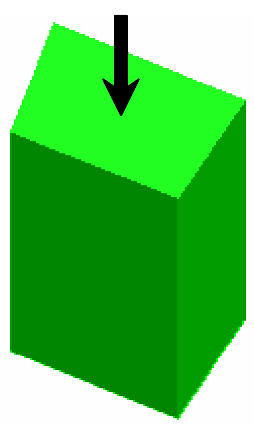


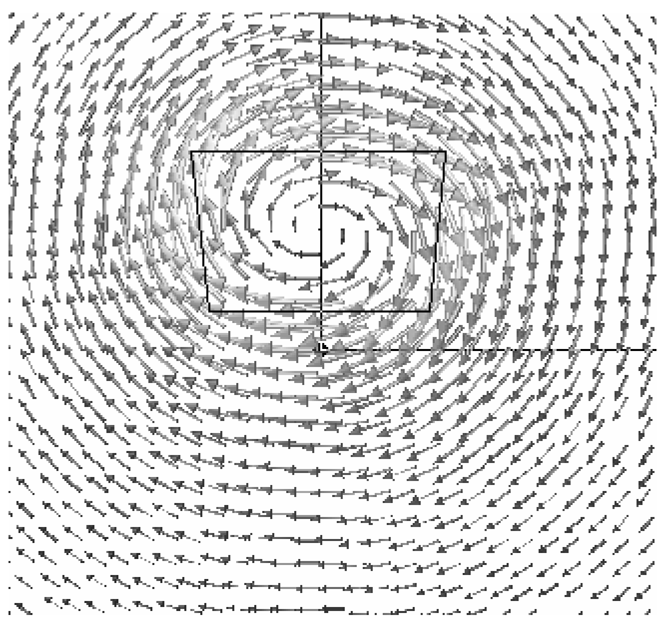
(a)



(b)

Figure 2.34. Magnetic Field for a Copper Bar. a) Copper Bar with Current Polarization, b) Magnetic Field for the Copper Bar in a)

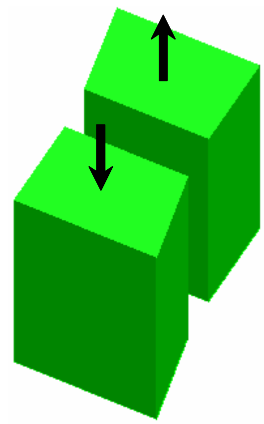




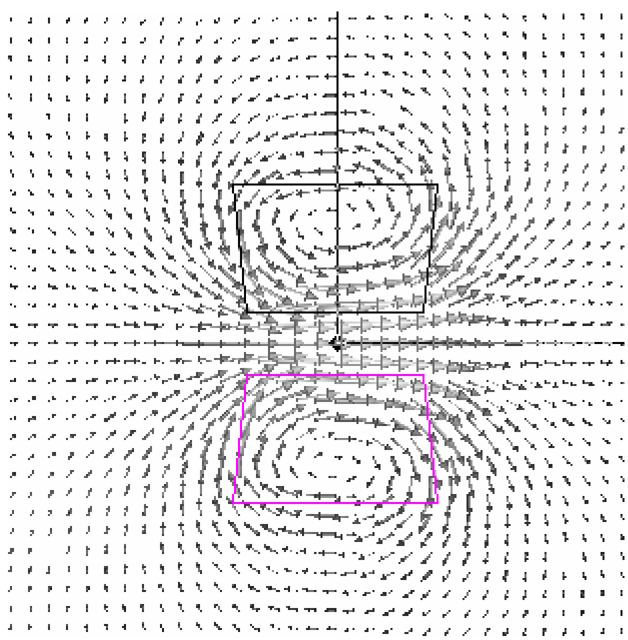
(a) (b)

Figure 2.35. Magnetic Field for a Copper Bar. Inverse Polarization a) Copper Bar with Current Polarization, b) Magnetic Field for the Copper Bar in a)

When the two copper bars of Figures 2.34 and 2.35 are placed facing each other as in Figure 2.36 they will experiment a repulsion force due to the opposite direction of the currents.



(a)



(b)

Figure 2.36. Magnetic Field for the Copper Bar Representing a Winding with an Air Core. a) Winding and Current Polarization, b) Magnetic Field of the Winding a).

2.1.9.2. Magnetic Field Generated by the Winding

The winding in the Berdut design has a core of a ferromagnetic material whose function is to concentrate the magnetic field. For Figures 2.37 and 2.38 the material of the windingcore was cold rolled steel and the current flowing in the winding was 380 A-turn.

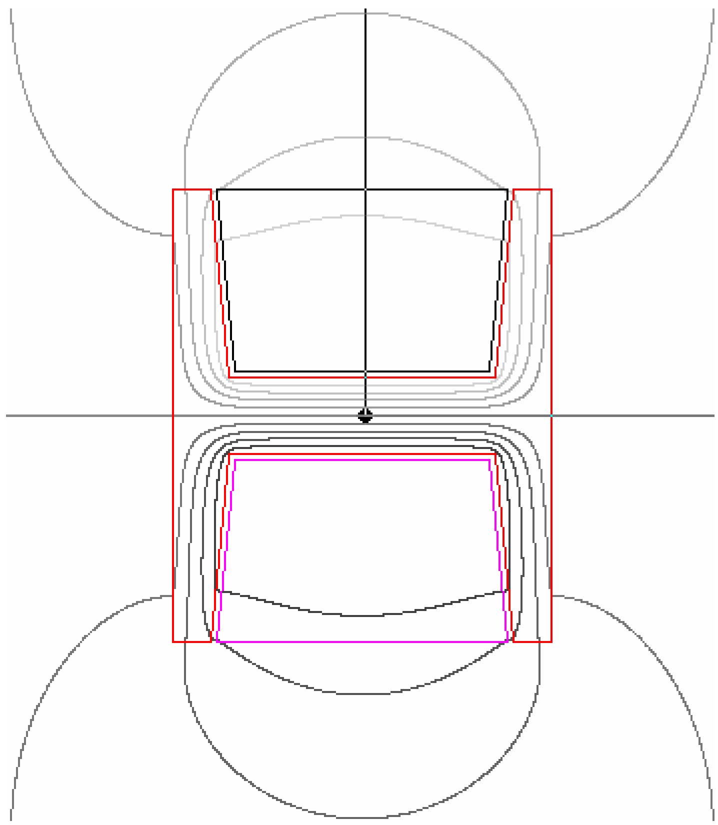


Figure 2.37. Flux Lines for the Winding.

The flux lines of the winding are mainly concentrated in the windingcore, this effect is related with the fact that the cold rolled steel is a ferromagnetic material of easy magnetization and demagnetization. The magnetic field generated after reorientation of the molecular magnets of the windingcore due to the magnetic field of the windings is added to it resulting in a stronger magnetic field.

The magnetic behavior of the winding can be associated to a rectangular permanent magnet and the north and south pole can be determined by the rule of the clock hands [32]:

— If the current flows clockwise the observer is looking at the south pole of the winding.

— If the currents flows counterclockwise the observer in looking the north pole of the winding.

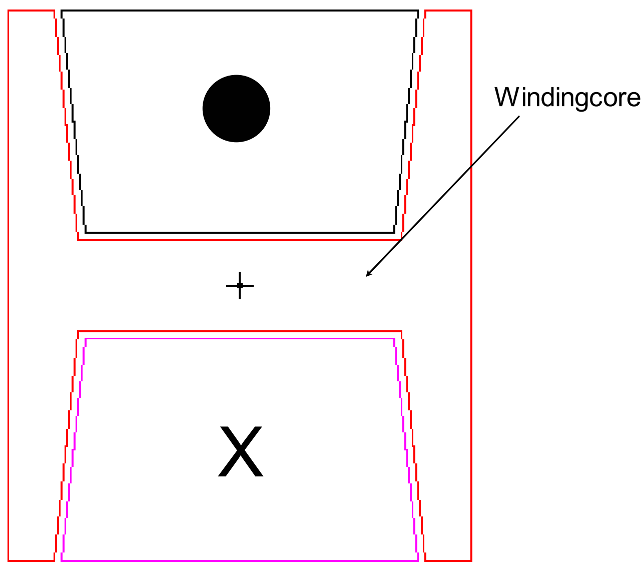


Figure 2.38. Winding Polarization.

Appling the clock hands rule to the winding with polarization as seen in Figure 2.38 the north pole is at the right side and the south pole is at the left side. This can be confirmed by Figure 2.39 where the magnetic field starts in north pole (right side) and ends in south pole (left side) For the case where the current polarization is inverse the north pole would be in the left side and the south pole in the right side and the direction of magnetic field would be exactly opposite to the direction in Figure 2.38.

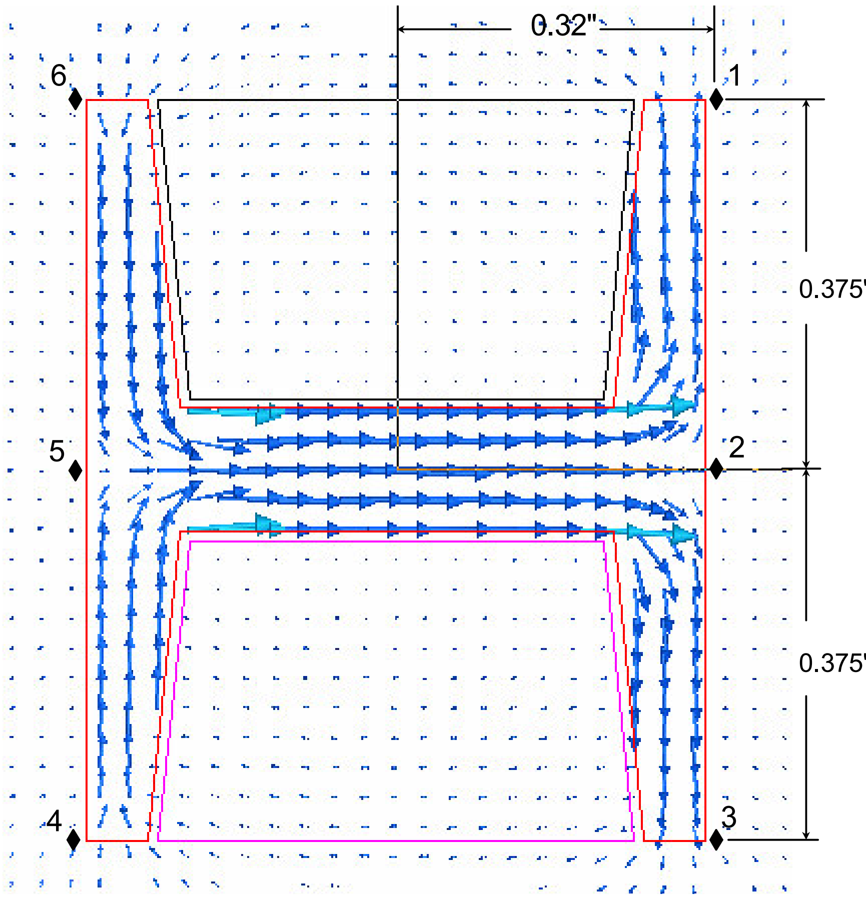


Figure 2.39. Magnetic Field. Winding

Table 2.14 indicates the magnitude of magnetic field in some points near the winding.

Table 2.14. Magnetic Field around the Winding.

Figure 2.30 point	**Magnetic Field Magnitude (T)**
1	6.5×10^{-12}
2	6.5×10^{-12}
3	6.5×10^{-12}
4	6.5×10^{-12}
5	6.5×10^{-12}
6	6.5×10^{-12}

The simulation based on Figure 2.38 indicates that the magnetic field inside the windincore is:

$$B_w = 2.96x10^{-1} \quad T$$

A winding can be represented by several wire loops close to each other and the rule for determining the direction of magnetic field generated by the winding is the right hand rule. This method is an alternative to the hand clock rule for determining the magnetic field directions. The direction of the magnetic field is always perpendicular to the wire and will be in direction of the right hand fingers would curl if they are wrapped around the wire with the thumb in the direction of the current. In the case of a wire loop applying the right hand rule shows that all parts of the loop contribute to the same direction of the magnetic field in the interior of the loop. The same will occur with the winding.

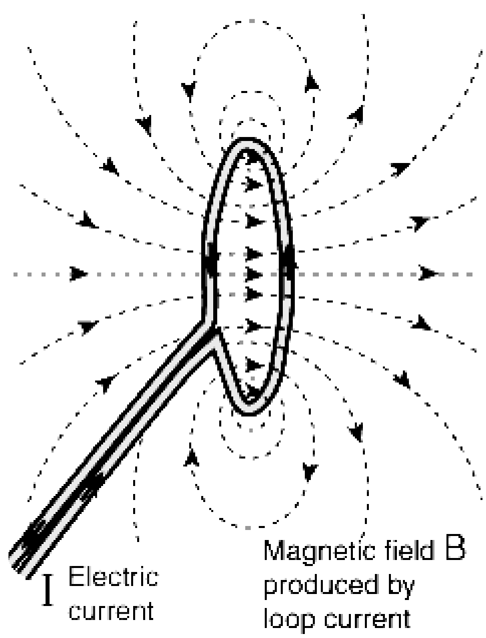


Figure 2.40. Magnetic Field Generated by a Current Loop.

Figure 2.40 confirms how the magnetic field has the same direction in the center of the loop. A winding is a set of wire loops and each loop contributes to the magnetic field generating a stronger magnetic field with the same current magnitude. The magnetic field is stronger in the center of the winding. In the case of winding of the Berdut design (Figure 2.38) the core acts as a field concentrator as can be seen in Figure 2.37 and this concentration causes an increment in the magnetic field. The behavior of the two solid copper bars is perfectly compatible with a real winding which validate the two copper bars as method for simulating the winding.

Inserting the winding of Figure 2.38 into the Final Configuration, the Berdut design is created and both magnetic fields will interact generating a force that moves the winding. The direction of this force is related with the current polarization in the winding and the direction of the magnetic field. The magnitude depends on the current magnitude and magnetic field magnitude. The direction of the force can be determined by the left hand rule. Controlling the current the velocity will be controlled. The dimensions of the Final Configuration and the winding remain the same.

2.2. Force Analysis

A wire with an electric current placed in a magnetic field will always be expulsed from the magnetic field. The direction of the expulsion — or force — is determined by the following left hand rule:

— The four fingers point to the direction of the current.

— The palm receives the magnetic field perpendicularly.

— The thumb will point to the force direction.

In the case of Berdut design the winding will experiment a force governed by the formula $\vec{F} = \vec{i}\, l\, x\, \vec{B}$ whose direction will depend on the current polarization in the winding and the direction of the magnetic. The objective of the Berdut design is to generate a force that permits a stable and continuous movement. For all this it is necessary to harmonize the direction of magnetic field generated by the geometry with the magnetic field generated by the winding. If both magnetic fields have the same direction the resulting magnetic field will be the optimal. It is important to clarify that the magnetic field of the geometry has a defined direction due to the magnetization direction of the permanent magnets. Observing the Figure 2.22 in a magnified view it is possible to confirm that the direction of the magnetic field changes through the geometry in accordance with the magnetization direction of the permanent magnets. Of course it is possible to change the magnetization direction of the permanent magnets but this change always has to create a north pole and a south pole interlaced through the configuration, however once the north and south pole are created, the direction of magnetic field will be fixed between a pair of tee's. On the other hand, the magnetic field of the winding can change its direction changing the current polarization. This means that it is possible to change the magnetic field direction of the winding in order to create attraction or repulsion between the tee's and the winding generating a movement or a brake system. If an attraction force is created the winding will be in movement but due to the changes in direction of the magnetic field through the configuration the current polarization must change in order to create attraction force. An important issue in the Berdut design is to find the exact point where the current polarization must change allowing a continuous movement in accordance with the attraction force. All this justifies a force analysis that determines the exact point for current polarization change and optimal force magnitude. The analysis of force will be conducted simulating some configurations in Maxwell 2D version 9 where the force and magnetic field will be calculated and analyzed. However without the possibility of change current polarization as the winding pass through the magnetic field the following force analysis is the initial step and it constitutes a preliminary effort for determining the optimal point of current polarization change.

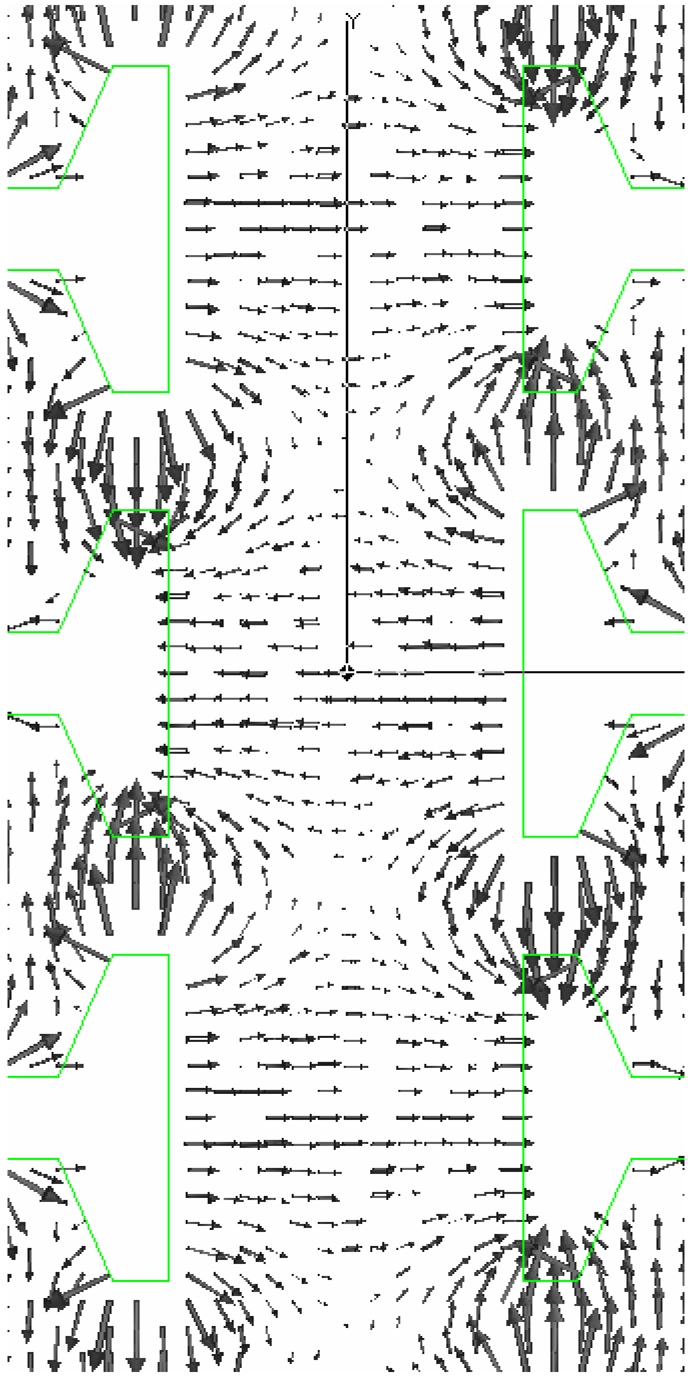


Figure 2.41. Changes in Magnetic Field Direction Through the Configuration.

2.2.1. Configurations for Simulations

The dimensions for the configurations remain the same. The details of dimensions are in Figures 2.12 and 2.21. The magnitude of the current for these simulations was 380 A-turn and its polarization is shown in the next Figure.

The force acting over the winding will be calculated for each configuration. It is important to reaffirm that the winding has three elements the superior copper bar, the inferior copper bar and the windingcore. The software program Maxwell 2D version 9 calculates the force on each component and then a vectorial addition is applied to the three forces giving the resultant force. The resultant force will be analyzed in magnitude and direction when pairs of tee's are added. The addition of pairs of tee's will allow to reach the final configuration where the analysis will be concluded. After this analysis a different analysis will take place on final configuration with different materials for the permanent magnets, tee's and windingcore. The analysis of the influence of different materials over the force is important because by this mean is possible to reduce the costs reaching simultaneously an optimal force in order to guarantee a continuous movement. The objective of the force analysis is to determine the influence of magnetic field in the magnitude and direction of the force exerted in the winding therefore the materials used in this analysis are not important. The importance of materials lies in cost reduction and how they influence in the magnitude of the force but the magnetic field direction depends just on the magnetization direction of permanent magnets and current polarization.

Table 2.15. Materials for the Force Analysis.

Component	Material
Tee	Cast Iron
Permanent Magnet	Ceramic 5
Windingcore	Cast Iron

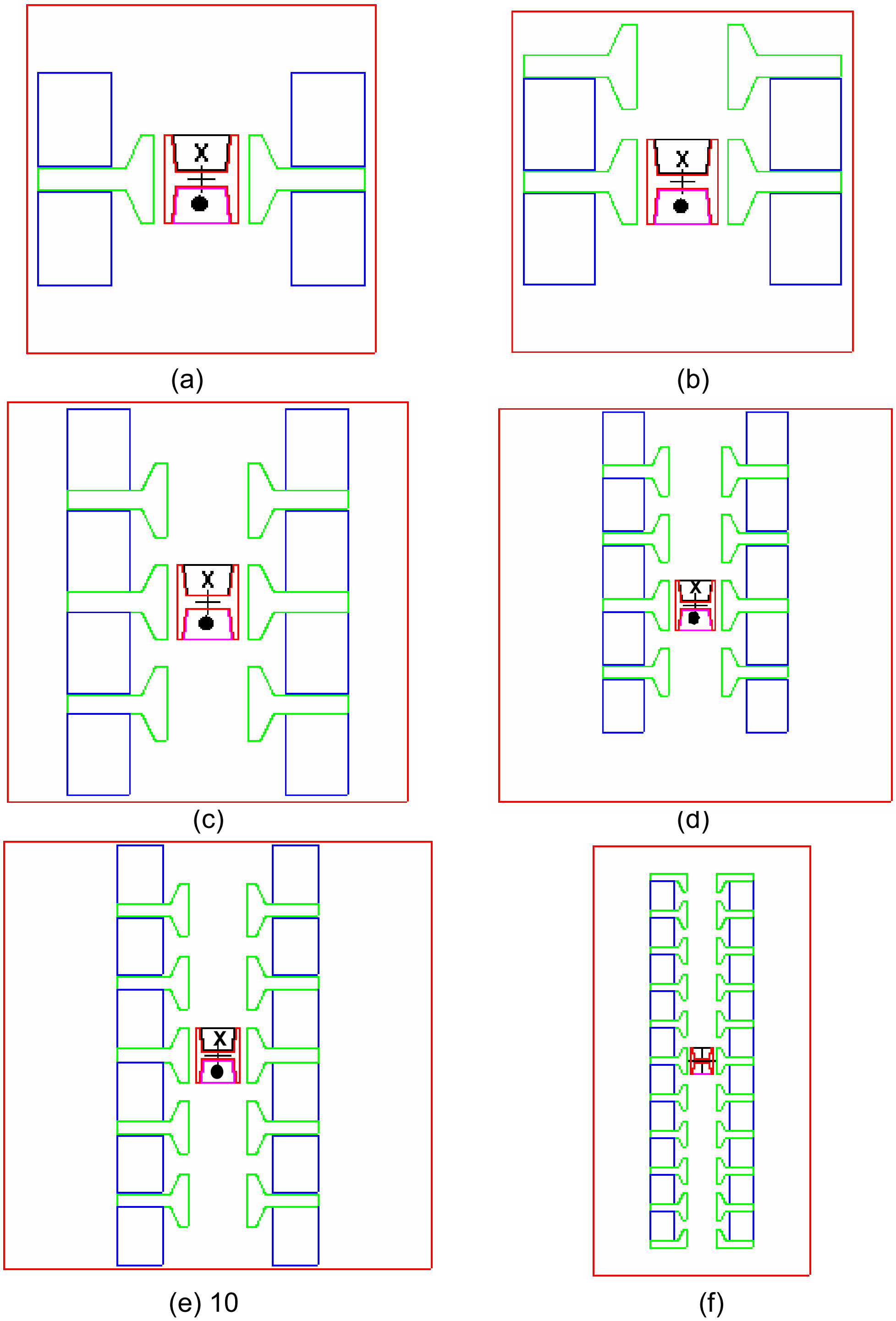
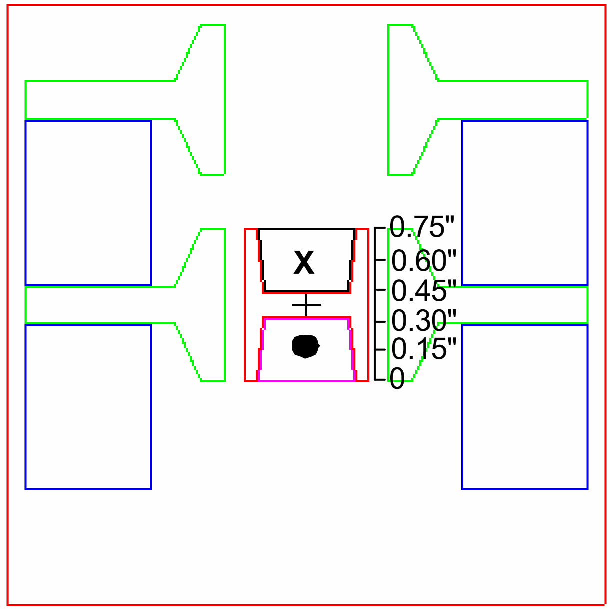
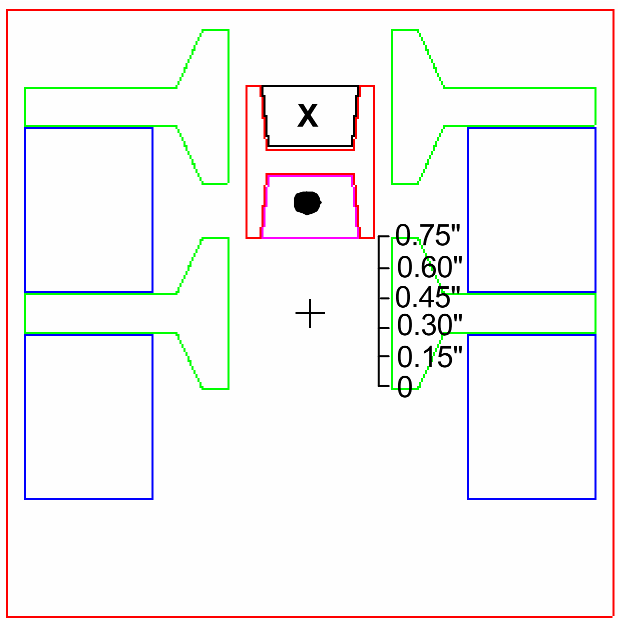


Figure 2.42. Configurations for Force. (a) 2 Tee's, (b) 4 Tee's, (c) 6 Tee's, (d) 8 Tee's, (e) 10 Tee's and (f) Final Configuration.



(a)



(b)

Figure 2.43. Example for Displacement. (a). Initial Position, (b) Final Position

During the force analysis the winding will be displaced through the magnetic field in each configuration. This displacement will be across the transverse dimension of the tee face that is 0.75 inches, the force will be calculated on five points therefore the displacement will be in steps of 0.75/5 = 0.15 inches. This displacement covers the entire uniform zone and the bending zones. The magnetic field will be the resulting field after the vectorial addition between the magnetic field of the configuration and the one of the winding.

During the force analysis just one winding was used because:

- All simulations are intended for determining the role of each element as well as the interaction between them and how each element can influence in the force magnitude and direction.

- With one winding it is possible to determine the behavior of the magnetic field after the insertion of the winding

- All the windings of the Berdut design are identical and the distance between them is the same. The only change in the windings is in current polarization. The changes in magnetic field direction through the configuration are fixed and just the direction of the magnetic field in the winding changes as a function of the current polarization. This implies that the behavior of each winding is exactly the same if a change in polarization is guaranteed in the correct point through the simulation distance.

The first two configurations are not relevant because the number of tee’s is low. However these two configurations are important because they allow to understand how the magnetic field influences in the direction and magnitude of the force exerted over the winding. After the force analysis some material were changed with the objective of exploring the influence of these in the force magnitude, this materials were choose based on costs, availability and the patent of Mr. Berdut.

Chapter 3

Simulation Results

The following simulations results correspond to the force analysis configurations in Figure 2.41 and the materials used in the configurations are listed in Table 2.15. The current for the simulations was 380 A-turn

3.1. Force Analysis Results

In the next Figures the magnitude and direction of the force are shown.

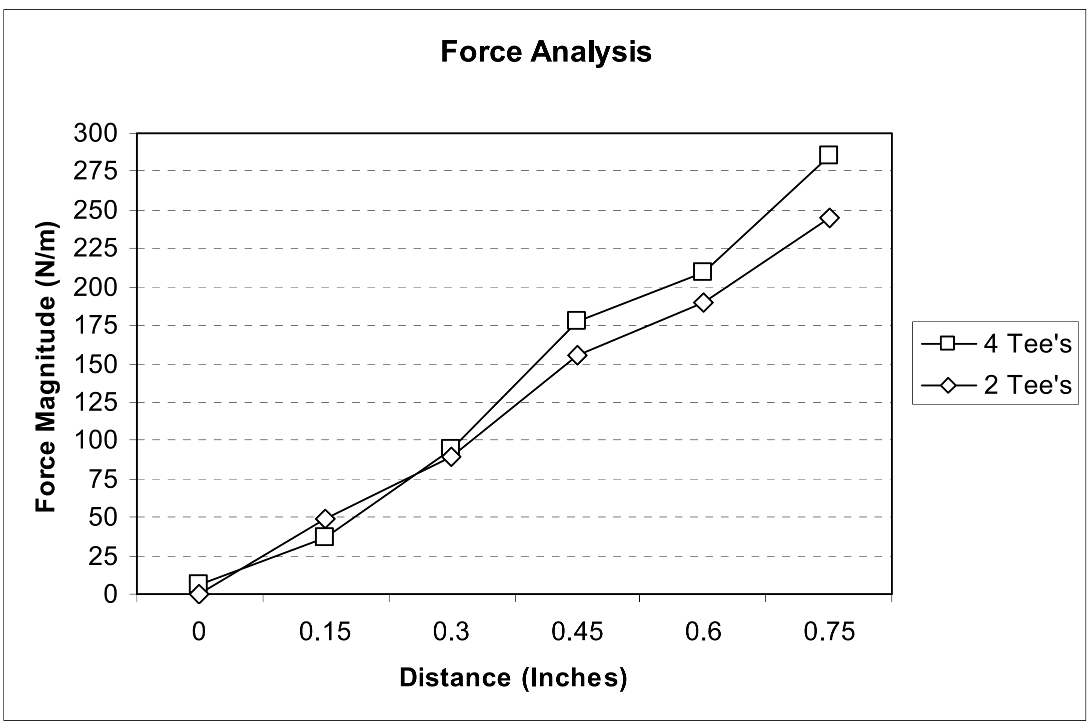


Figure 3.1. Magnitude of the Force for the first two Configurations.

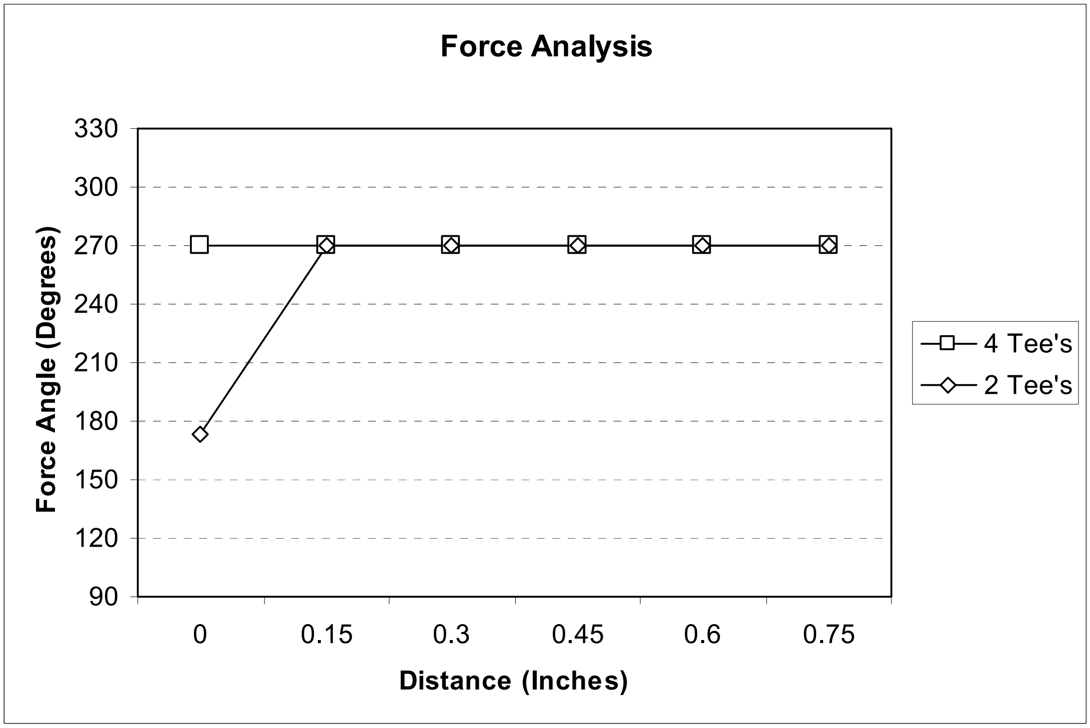


Figure 3.2. Direction of the Force for the two first Configurations

Two and four tee’s are a very low quantity of tee’s but this configurations are useful because they allow to understand some facts regarding the insertion of the windingcore and how complex can be the relation between force over the winding and the magnetic field responsible for this force. This complexity is more accentuated when the number of tee’s is incremented. However there are some characteristics that can be noticeable through the simulations.

Regarding the magnitude of the force in Figure 3.1 it is apparent that the influence of the tee’s is not relevant because the magnitudes of the force are very similar through the distance. However it is important to notice some factors:

— In the 0 point the magnitude is almost zero because there is equilibrium of forces and each tee is attracting the windingcore resulting this in a total force of zero and the direction of the force is not important, in the 0.75 point the force is a maximum. In all the points the force direction the same, 270 degrees. In Figure 3.4 the resultant force is shown for all the points for the case of 4 tee’s.

- The windingcore is very important because its material, cast iron, concentrates the magnetic field incrementing its magnitude regardless the distance or number of tee’s. In any point the windingcore is always being attracted to the tee faces and concentrating the magnetic field. In Figure 3.1 the trend of the force magnitude is to increment as the winding is being removed from the tee’s. This is because at any point the material of the windingcore concentrates the magnetic field incrementing it and acting as “amplifier” of magnetic field becoming it the main contributor to the magnitude of the force. As the amplifier effect takes place a reconfiguration of the magnetic field also takes place around the windingcore this reconfiguration makes very difficult the behavior prediction of the force and affects the symmetry in magnetic field presented by the configuration without the winding. Incrementing the number of tee’s this prediction is even more difficult.

- In the case of four tee’s the contribution from superior and inferior copper bars to the magnitude is not relevant from 0 until 0.30 inches because in any point in this interval the force generated by a copper bar is always opposite to the one generated by the other copper bar. However from 0.45 and so on the superior copper bar is under the influence of the magnetic field in the two extra tee’s where the force generated is in the same direction of the force in the inferior copper bar. The windingcore is being attracted simultaneously by the inferior pair of tee’s and superior pair of tee’s but in general the attraction exerted by the superior pair of tee’s it is not enough to change the direction of the force.

— For the case of two tee's in 0.30 inches the superior copper bar is in the bending zone as seen in Figure 3.3. In the bending zones the magnetic field direction changes resulting in a dramatic reduction of the field. From 0.30 inches the force exerted over the superior copper bar begins to be irrelevant because the magnetic field magnitude is low and the total force exerted over the winding is due to the inferior copper bar and the windingcore resulting this in an increment of the force due to the elimination of the opposite force of the superior copper bar. From 0.60 the inferior copper bar is now in the bending zone and its contribution to the force magnitude is almost zero. This also confirms that the main contributor to the force magnitude is the windingcore and how this force is bigger because the windingcore is being attracted for the tee's as the winding is removing from them.

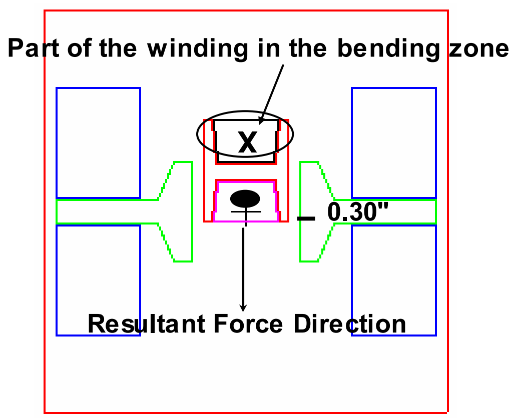


Figure 3.3. Effect of the Bending Zones.

— In Figure 3.1 from 0.45 inches up to 0.75 inches the difference in magnitude of the forces is bigger because for the case of 4 tee's, from 0.45 the top bar is under the influence of the uniform zone associated with the two extra tee's and the field in this zone is in the opposite direction. Applying the rule of left hand before mentioned the force exerted over the superior bar is now in the same direction (270 degrees) of the force exerted in the inferior copper bar and a stronger force is reached from 0.45 until 0.75 inches. Figure 3.4 illustrates this behavior of the force.

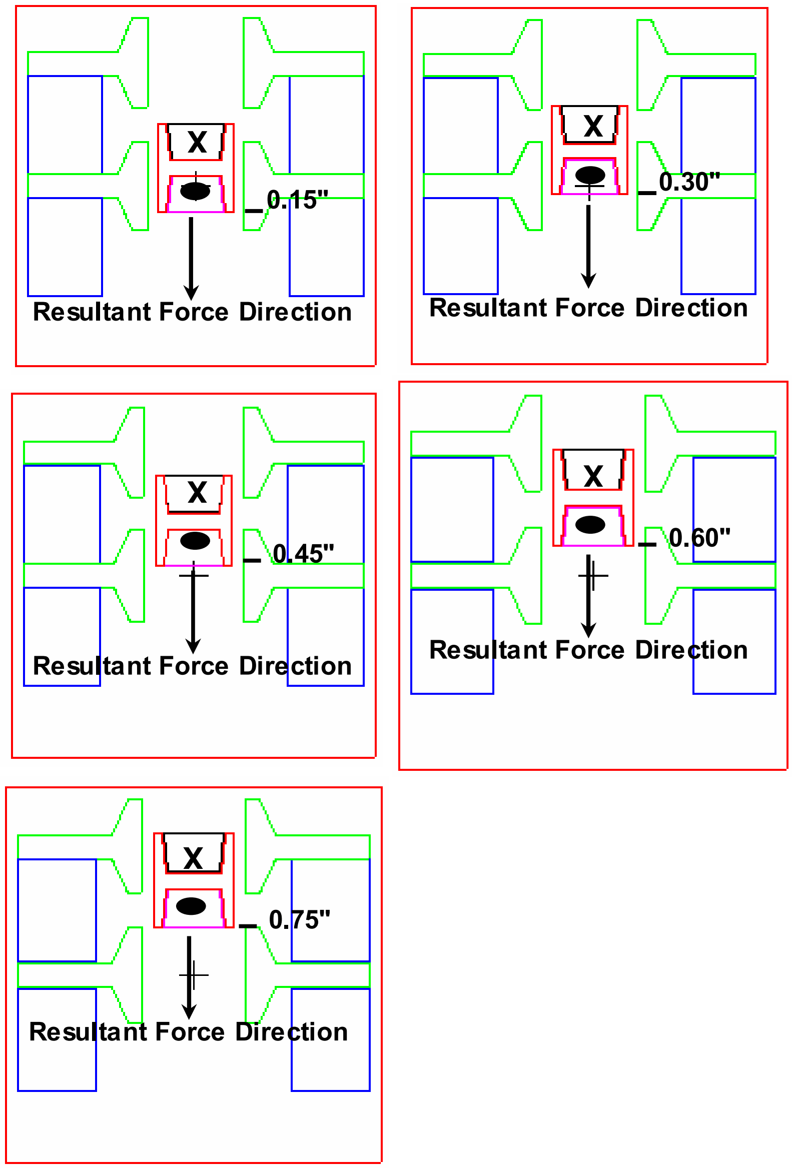


Figure 3.4. Force Direction for 4 tee's Case from 0.15 Inches to 0.75 Inches.

In the next Figure the amplifier role of the windingcore is confirmed and also the reconfiguration of the magnetic field around the windingcore is evident.

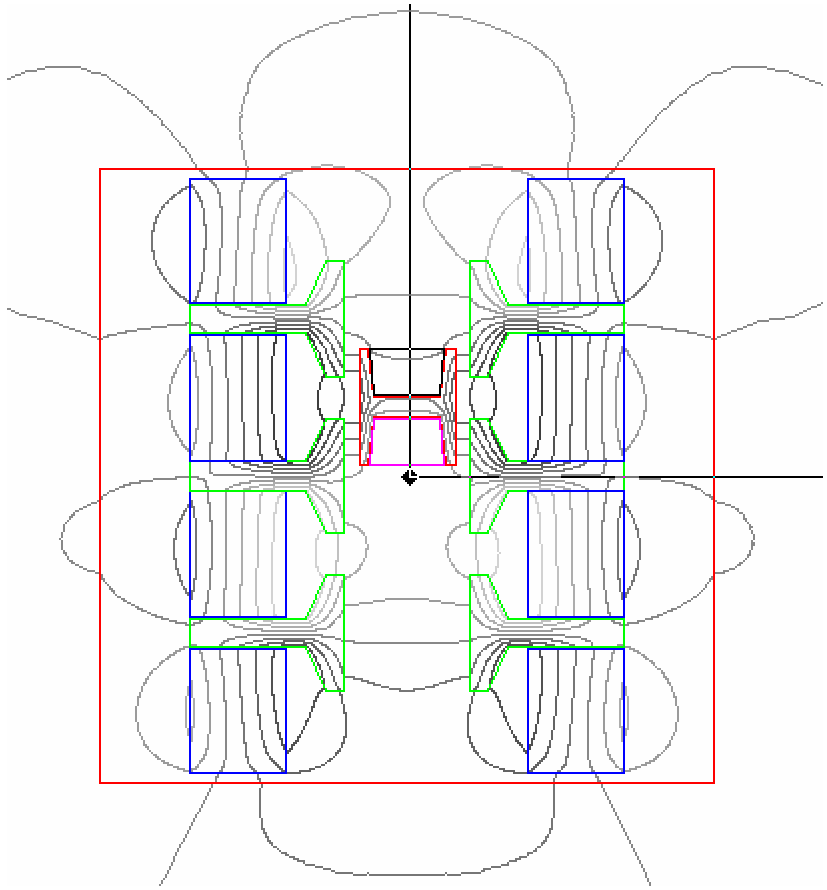


Figure 3.5. Amplifier Role of the Windingcore.

The next Figures present the results for the other configurations. All the simulations were run using an error percent of 0.5 % as a convergence criterion. In Figure 3.6, the magnitude of the force for 8 and 10 tee's is almost the same for the final configuration. This reveals that with the final configuration it is possible to predict the behavior of a longer railway. The effect over the force after adding more than 6 tee's is insignificant and the application of a Design of Experiment (DoE) analysis is not necessary.

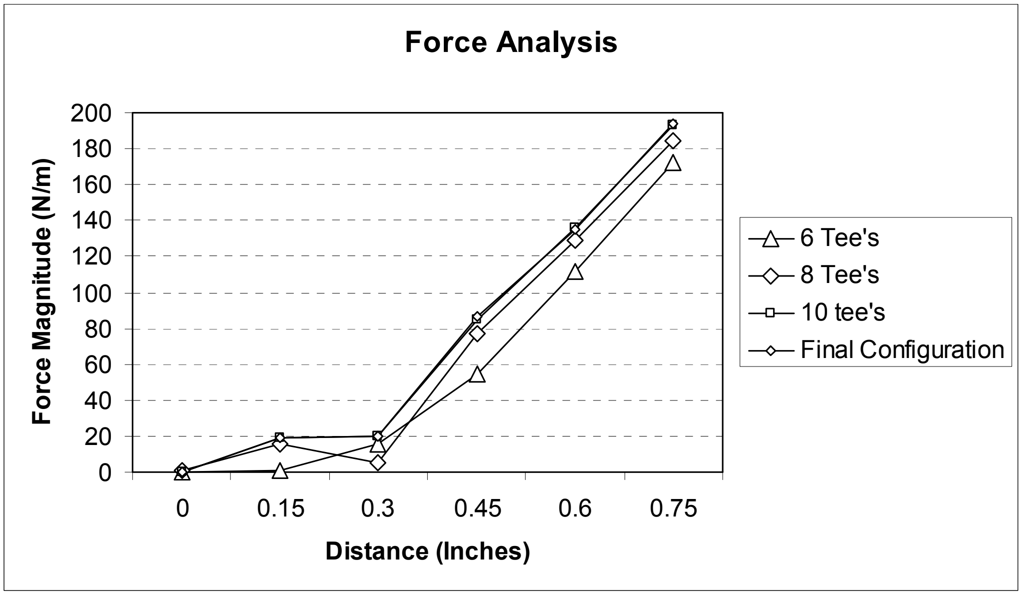


Figure 3.6. Magnitude of the Force in the Cases 6, 8, 10 Tee’s and Final Configuration.

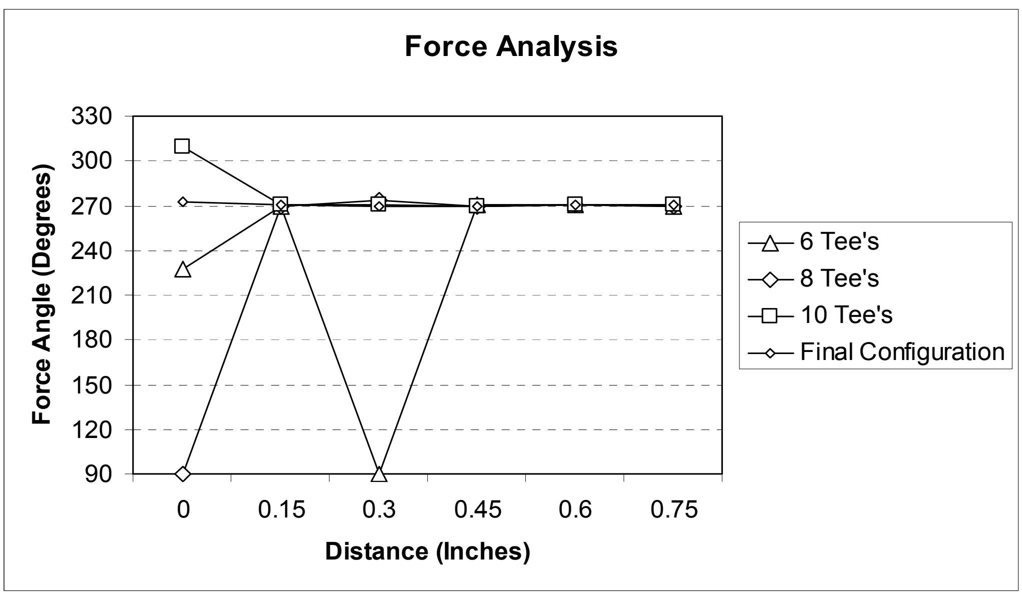


Figure 3.7. Direction of the Force In the Cases 6, 8, 10 Tee’s and Final Configuration.

In Figure 3.7 for all the cases in the point 0 the angles are irrelevant because the all force magnitudes are almost zero. From 8 tee’s up to final configuration changes in direction are not presented. Figure 3.6 presents some common characteristics with Figure 3.1: in the first point the force is almost zero and in the last point it is maximum, the trend is to grow as the winding is being removed from the tee's. Also a general reduction in the force respect to the Figure 3.1 is revealed. This reduction indicates that the effect of the interaction between the magnetic fields is significant however the magnitude of the force is still useful. The values of the force are in the next Tables.

Table 3.1. Force for 2 and 4 Tee's.

	Number of Tee's			
	2		**4**	
Position (Inches)	**Magnitude (N/m)**	**Direction (Degrees)**	**Magnitude (N/m)**	**Direction (Degrees)**
0	0.01159	172.989	6.36924	269.8
0.15	48.7072	270.006	36.2006	269.895
0.30	89.2932	269.993	93.8629	269.984
0.45	155.118	270	177.41	270.012
0.60.	189.838	270.005	209.149	269.979
0.75	245.034	269.996	285.609	269.998

Table 3.2. Force for 6 and 8 Tee's.

	Number of Tee's			
	6		**8**	
Position (Inches)	**Magnitude (N/m)**	**Direction (Degrees)**	**Magnitude (N/m)**	**Direction (Degrees)**
0	0.05527	227.689	0.8075	89.9052
0.15	0.685017	269.577	15.86	269.936
0.3	15.5514	89.9682	4.9	274.045
0.45	54.4324	270.267	77.3692	269.831
0.6	111.436	270.024	128.617	270.115
0.75	172.016	269.94	184.285	269.956

Table 3.3. Force for 10 Tee's and Final Configuration.

	Number of Tee's			
	10		Final Configuration	
Position (Inches)	Magnitude (N/m)	Direction (Degrees)	Magnitude (N/m)	Direction (Degrees)
0	0.0291	309.585	0.0878	272.429
0.15	19.2794	270.117	19.1439	270.281
0.3	19.5868	270.414	19.7908	269.646
0.45	84.6736	269.907	86.2444	269.293
0.6	135.564	270.008	135.468	270.069
0.75	193.048	270.021	194.106	270.024

3.2. Initial Point Analysis

The winding must be placed in a point where the movement begins in a stable and continuous way. In order to explore with more accuracy the force in final configuration a simulation was run with more points using parametric simulation analysis between 0.75 and -0.75 with a step of 0.75 inches in Maxwell 2D with a percent of error of 0.5 % as a convergence criterion.

For determining the optimal point is necessary to know the mass of the vehicle as well as a dynamic analysis. For all this the initial point analysis here presented is just a preliminary step because to date a big scale model is not available and the software program is not able to run a type of simulation where a change in current polarization is applied simultaneously to the winding as it pass through the magnetic field. From Figure 3.8 the recommended point will be a point in the interval 0 to 0.15 inches. In this interval the force is sufficiently small and can give a comfortable movement to the winding. In Figure 3.8 a big change in the force is revealed. For the point 0.30 to the point 0.75 the change in force is 173 N/m this is in just 0.45 inches a big acceleration is expected. The current magnitude must be controlled in order to control the abrupt increments of force.

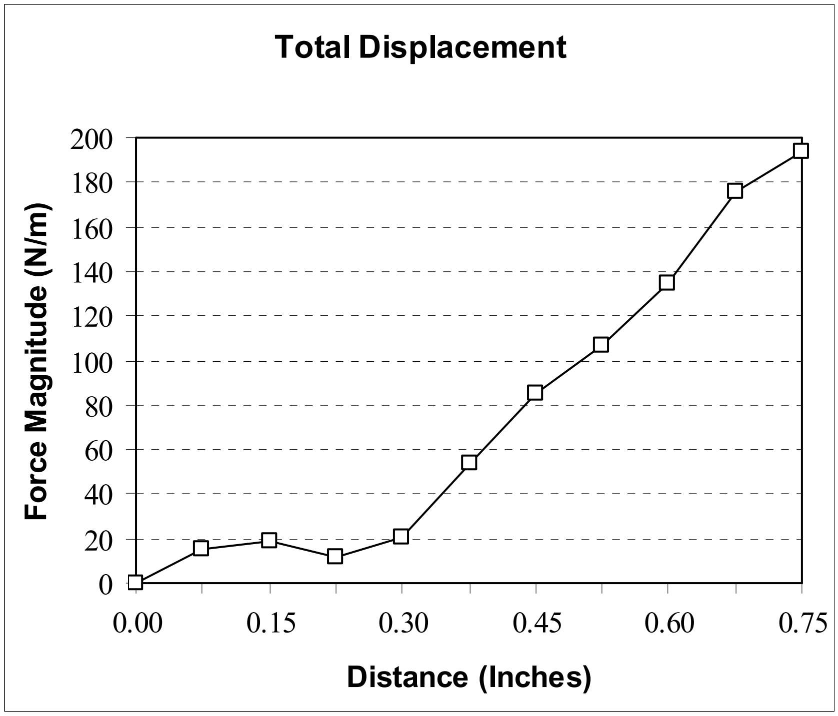


Figure 3.8. Force Magnitude for Final Configuration.

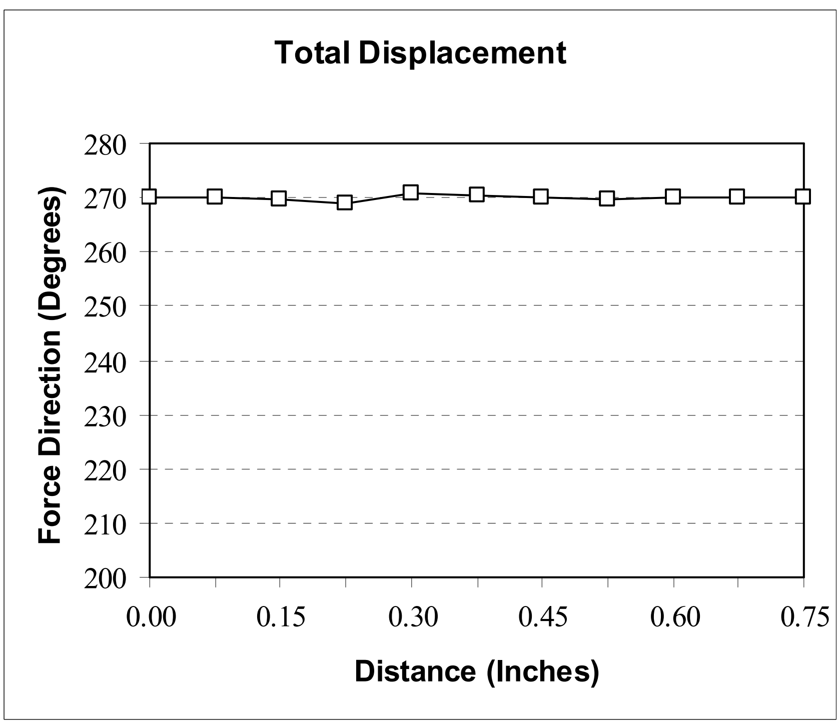


Figure 3.9. Force Direction for Final Configuration

Table 3.4. Force for Final Configuration.

Position (Inches)	Magnitude (N/m)	Angle (Degrees)
0	0.092523	269.9265
0.075	15.28602	270.23
0.15	18.40403	269.6549
0.225	11.64071	268.9622
0.3	20.82795	270.742
0.375	53.42522	270.4731
0.45	85.53144	270.2029
0.525	106.9995	269.8316
0.6	134.8765	270.1614
0.675	175.5011	270.0722
0.75	193.8641	269.9384

3.3. Point of Current Polarization Change

In order to determine the point where the current polarization must take place for guaranteeing a stable and continuous movement without changes in directions, the force in some additional points was calculated. Figure 3.10 is a portion of the final configuration and the details of this movement are presented. The step used in the simulations was 0.075 inches. In the next Figures the direction and magnitude of the force are listed for the total displacement. The simulations were run with error percent of 0.5 % as a convergence criterion.

Abrupt changes in the direction of the force will cause abrupt reduction of velocity with its inherent danger for the system. Movement in one direction is a must of the system regardless the magnitude of the force. An effective and secure brake system is also a must. The brake system can be implemented changing the polarization of the current and eliminating the abrupt changes in the current magnitude. This can be achieved using a control system for magnitude and direction of the current.

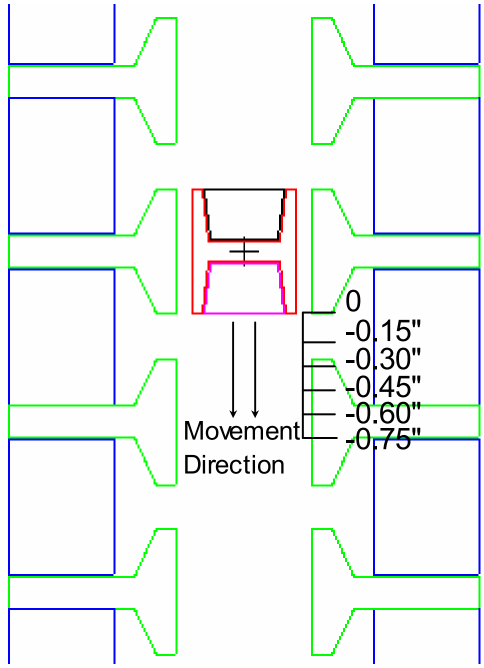


Figure 3.10. Movement Details for Current Polarization Change

In Figure 3.11 the symmetry in the force magnitude is obvious and this indicates that the magnetic field interaction in the winding presents symmetry in the distance of simulation with the specific current polarization used in the winding. In Figure 3.12 the change of direction at the point -0.15 is also obvious and reveals that the symmetry is just in magnitude. The symmetry of Figure 3.11 can be explained using two points, for example, the points 0.45 and -0.45 inches. In Figure 3.13 the flux lines for the inferior copper bar in the part (a) are very similar to the ones of superior copper bar in the part (b) and the flux lines of superior copper bar in part (a) are very similar to the ones of inferior copper bar in the part (b). These similarities are the result of the symmetry of magnetic field and the current polarization.

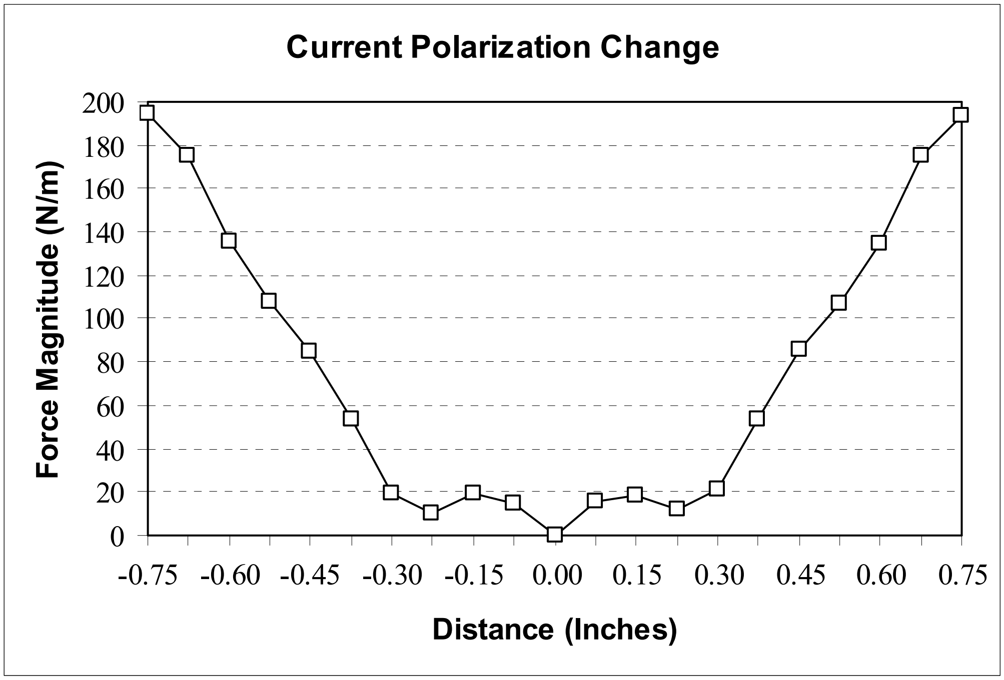


Figure 3.11. Force Magnitude for Current Polarization Change.

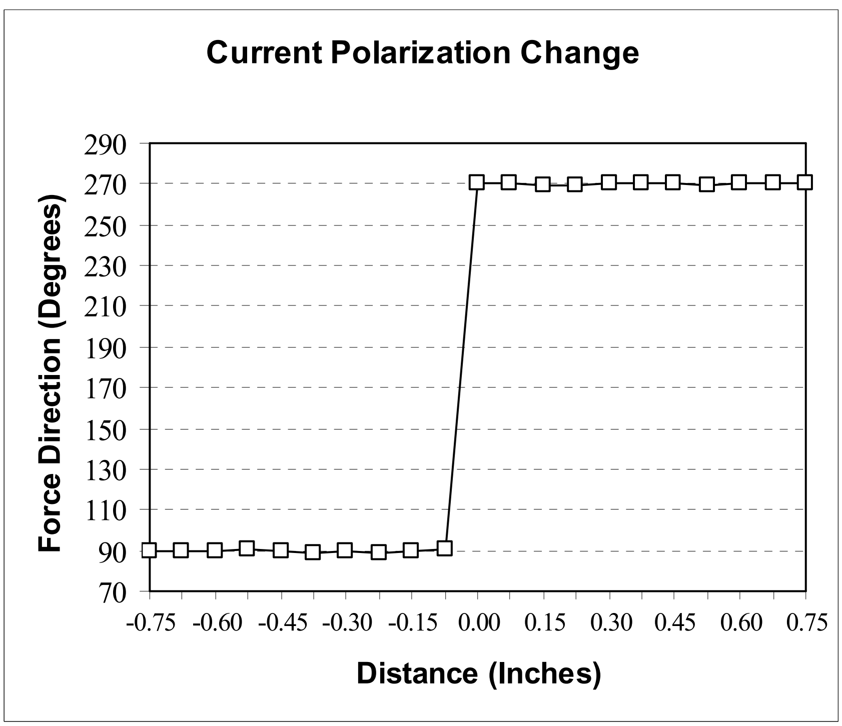


Figure 3.12. Force Direction for Current Polarization Change

The exact values for magnitude and direction are presented in the next Table.

Table 3.5. Force for the Total Displacement.

Position (Inches)	Magnitude (N/m)	Angle (Degrees)
-0.75	194.707	89.9258
-0.675	175.141	89.8993
-0.6	135.709	90.1197
-0.525	107.431	90.1696
-0.45	85.0328	89.975
-0.375	53.0673	89.0276
-0.3	19.5791	89.9716
-0.225	10.4715	89.1461
-0.15	19.5313	89.7569
-0.075	15.166	90.241
0	0.092523	269.9265
0.075	15.28602	270.23
0.15	18.40403	269.6549
0.225	11.64071	268.9622
0.3	20.82795	270.742
0.375	53.42522	270.4731
0.45	85.53144	270.2029
0.525	106.9995	269.8316
0.6	134.8765	270.1614
0.675	175.5011	270.0722
0.75	193.8641	269.9384

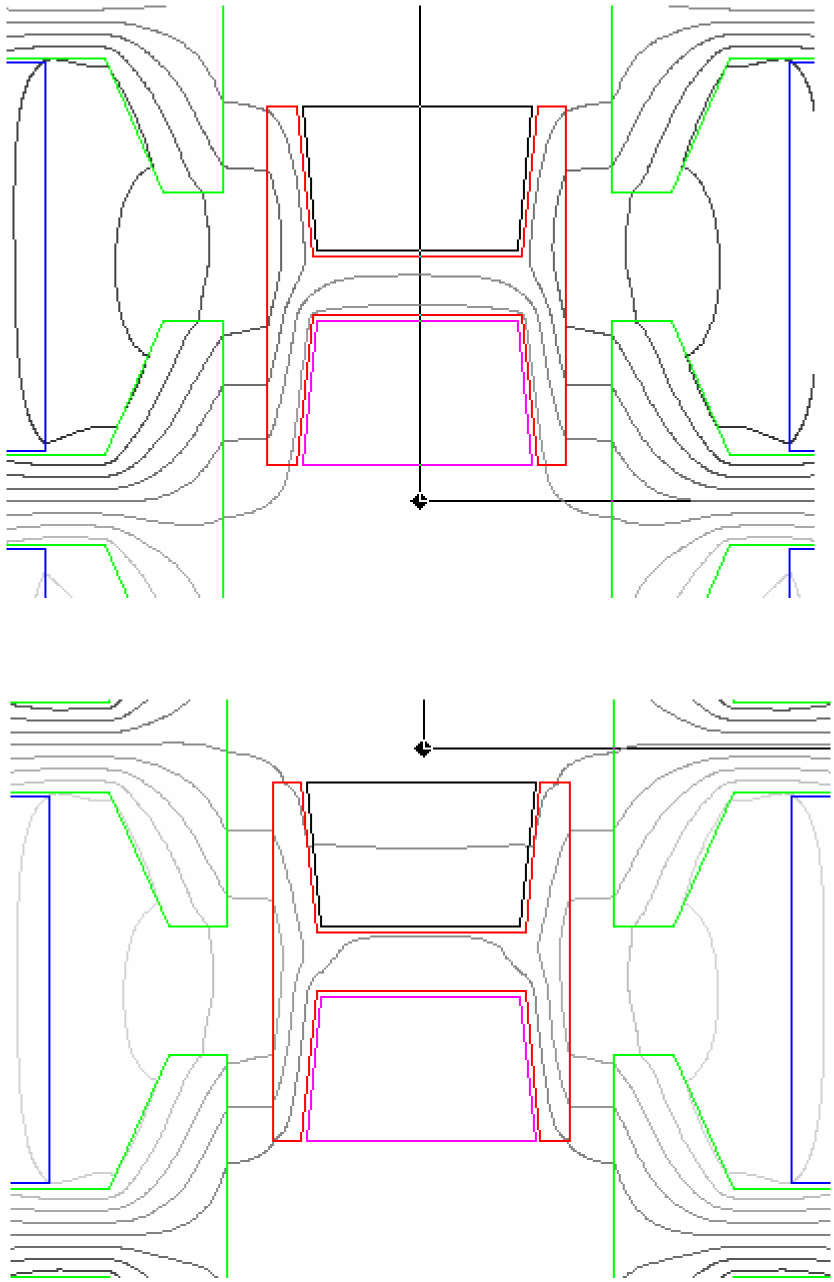


Figure 3.13 Flux Lines for the points 0.45 and – 0.45 inches. a) Flux Lines for 0.45 Inches, b) Flux Lines for -0.45 Inches.

Regarding the Figure 3.12 in the interval -0.075 to 0.075 there is an abrupt change in direction. This is related with step of 0.075 for the parametric simulations, with a lesser step the change in polarization will trend to occur at 0 point. The change in direction implies a sudden velocity reduction which is not allowed for security reasons. All this reasons suppose a point in the interval -0.075 to 0.075 as an optimal candidate for current polarization change. Analyzing Figure 3.11 the point -0.075 has a low magnitude force which reinforce this point as candidate.

As have been said a complete analysis must include a dynamic simulation however a set of simulations were run over the final configuration changing the current polarization at -0.075 point and the results are valid as a preliminary step in the establishment of a continuous movement which implies that changes in the direction force are not allowed.

With the polarization change the magnetic field of the winding also changes in direction and applying the clock hands rule, the direction of the magnetic field can be determined. In the point -0.75 the inferior copper bar will be in the bending zone but the force exerted over the superior copper bar is in the direction of movement. In general through the interval -0.075 to -0.75 the magnetic field of the configuration present the same direction of the magnetic filed generated by the winding after the current polarization. This generates an increment of the magnetic field. Also the concentration effect of the windingcore contributes to this increment. With the increment of the magnetic field an increment in the force can be expected.

The increment of the force and the current polarization change were analyzed using parametric simulation with an error percent of 0.5 % as a convergence criterion.

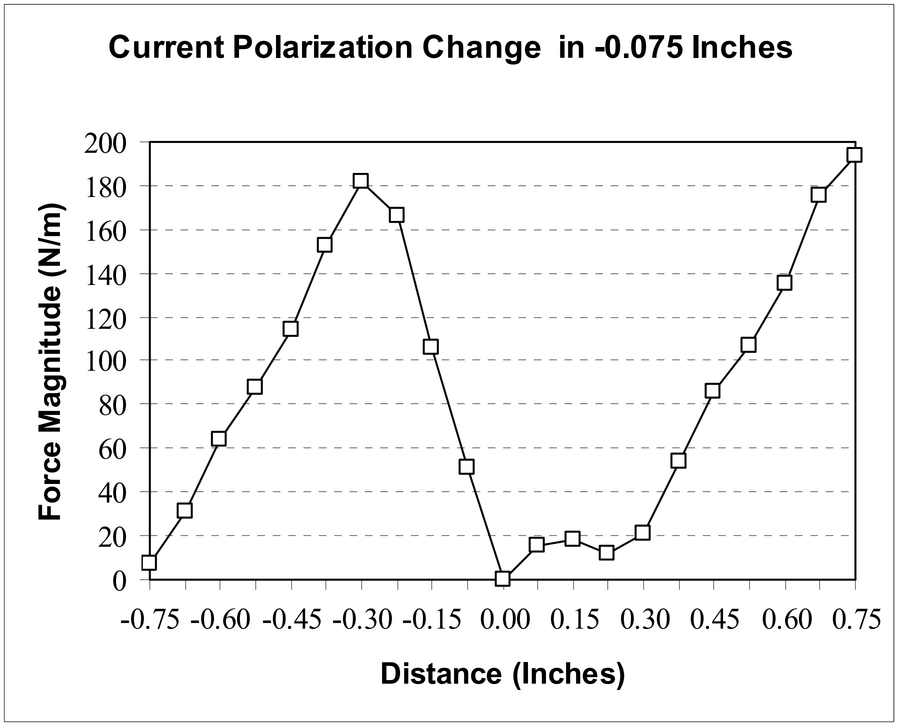


Figure 3.14. Force Magnitude. Current Polarization Change in -0.075 inches.

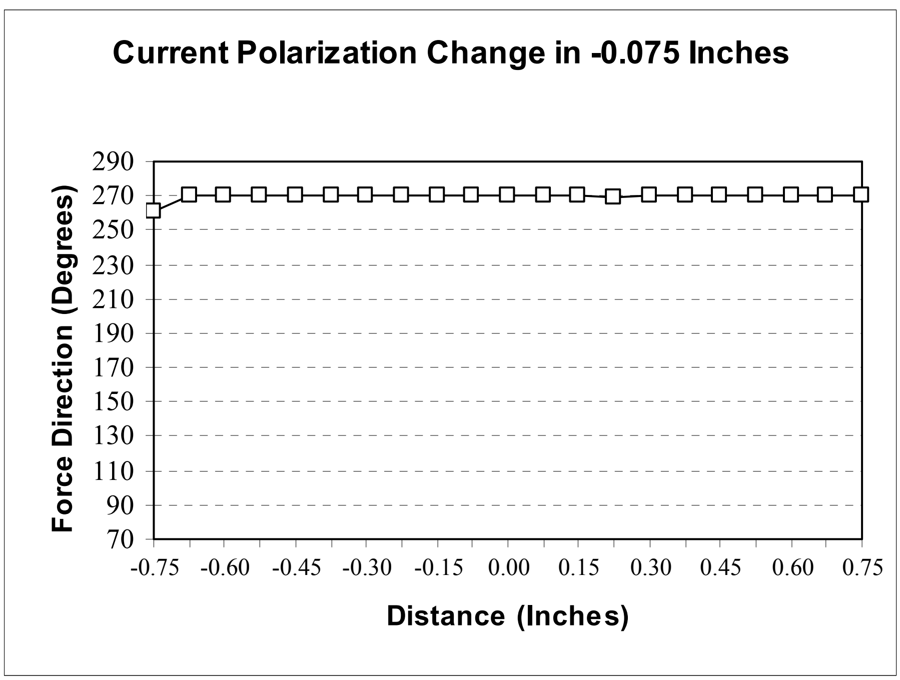


Figure 3.15. Force Direction. Current Polarization Change in -0.075 inches.

The exact values are listed in the next Table.

Table 3.6. Force for Current Polarization Change.

Position (Inches)	Magnitude (N/m)	Angle (Degrees)
-0.75	7.177	261.093
-0.675	31.047	270.612
-0.6	64.035	270.568
-0.525	87.874	270.226
-0.45	114.408	270.383
-0.375	152.552	269.760
-0.3	182.134	269.868
-0.225	166.241	269.895
-0.15	106.113	269.913
-0.075	50.794	269.888
0	0.093	269.926
0.075	15.286	270.230
0.15	18.404	269.655
0.225	11.641	268.962
0.3	20.828	270.742
0.375	53.425	270.473
0.45	85.531	270.203
0.525	106.999	269.832
0.6	134.877	270.161
0.675	175.501	270.072
0.75	193.864	269.938

In Figure 3.14 the behavior of the force suggests again big accelerations in small distances which imply a movement not allowed for security and comfort reasons. This characteristic can be eliminated controlling the current in the winding in such a way that a slow increment must be guaranteed. Simultaneously with the small increments in current small increments in force must be reflected. All this justifies a future exploration of a control system for the current

3.4. Materials Effect in Berdut Design

The materials of the Berdut design are the core of the design because functions like generation and concentration of magnetic field are only possible using the adequate materials. This means that the force magnitude is directly affected by the materials of the components and this effect depends on the characteristics of the materials. Fundamental characteristics of Berdut design like concentration and generation of magnetic field are directly related with relative permeability for the tee's and windingcore and with Br for the permanent magnets. The more relative permeability and Br the more magnitude of the force. This relation between material and magnitude force makes possible a good prediction of force behavior and eliminates the necessity of a DoE analysis.

The cost of a permanent magnet is directly related with the magnetic characteristics of the material used in its construction. The NdFeB presents the bigger B_r but the cost of this material is very high. By cost reasons is necessary a balance between the permanent magnet material and the tee's and windingcore materials because using materials with high relative permeability the concentration of the magnetic field will cause an increment of the magnetic field without the use of NdFeB. As the magnetic field can be incremented without the use of a high cost permanent magnets the NdFeB permanent magnets were eliminated of the analysis. In the next Figures changes in the materials were implemented in the final configuration. These changes are explained in the Tables 3.7, 3.8 and 3.9. All the simulations were run with an error percent of 0.5 % as a convergence criterion using parametric analysis in Maxwell 2D version 9.

Table 3.7. Materials for all the cases

	Material							
Component	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**case 5**	**Case 6**	**Case 7**	**Case 8**
Tee	Cast Iron	Cast Iron	Cast Iron	Cast Iron	Iron	Iron	Iron	Iron
Windingcore	Cast Iron	Cast Iron	Cold Rolled Steel	Cold Rolled Steel	Iron	Iron	Cold Rolled Steel	Cold Rolled Steel
Permanent Magnet	Ceramic 5	Alnico 5	Ceramic 5	Alnico 5	Ceramic 5	Alnico 5	Ceramic 5	Alnico 5

Table 3.8. Force for the cases 1, 2, 3 and 4

	Force		Force		Force		Force	
Position (Inches)	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**
-0.75	7.177	261.093	34.890	270.314	7.994	270.110	43.430	266.646
-0.675	31.047	270.612	48.510	269.894	27.502	269.583	52.400	269.996
-0.6	64.035	270.568	65.790	269.969	59.164	269.971	67.319	271.898
-0.525	87.874	270.226	80.783	270.021	92.099	270.245	83.842	269.029
-0.45	114.408	270.383	95.203	270.013	126.346	270.039	100.240	270.020
-0.375	152.552	269.760	111.203	270.017	161.909	270.029	116.635	270.426
-0.3	182.134	269.868	122.099	269.874	193.985	269.946	124.326	270.374
-0.225	166.241	269.895	102.255	270.001	172.400	269.910	100.472	269.750
-0.15	106.113	269.913	62.602	270.049	108.586	270.218	60.367	269.430
-0.075	50.794	269.888	28.380	270.161	49.819	269.570	26.925	267.962
0	0.093	269.926	0.057	354.853	0.139	299.120	0.163	150.100
0.075	15.286	270.230	24.552	270.068	27.440	269.581	37.047	270.202
0.15	18.404	269.655	39.515	270.118	30.720	270.828	55.687	270.064
0.225	11.641	268.962	50.282	270.118	19.960	271.416	62.409	269.984
0.3	20.828	270.742	61.268	270.196	20.329	270.006	68.754	269.724
0.375	53.425	270.473	80.639	270.204	47.628	270.881	83.982	269.891
0.45	85.531	270.203	98.242	269.890	80.398	270.491	101.612	268.321
0.525	106.999	269.832	111.754	270.018	113.110	270.584	117.256	268.551
0.6	134.877	270.161	127.720	270.039	150.565	269.908	136.279	268.050
0.675	175.501	270.072	145.691	270.988	189.839	269.693	150.608	270.624
0.75	193.864	269.938	148.534	269.988	204.800	270.124	146.605	270.211

Table3.9. Force for the cases 5, 6, 7and 8.

	Case 5		**Case 6**		**Case 7**		**Case 8**	
	Force		**Force**		**Force**		**Force**	
Position (Inches)	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**	**Magnitude (N/m)**	**Angle (Degrees)**
-0.75	11.514	89.744	64.796	269.600	13.671	67.260	58.540	269.558
-0.675	18.872	271.254	75.359	270.163	19.687	271.125	69.610	270.170
-0.6	69.424	270.438	92.051	270.953	73.310	271.562	89.714	269.715
-0.525	126.463	269.442	111.827	269.810	124.063	267.748	107.859	270.098
-0.45	182.774	270.562	130.141	270.450	178.218	271.660	127.661	269.886
-0.375	247.295	269.535	153.181	270.003	245.793	269.487	143.911	270.014
-0.3	292.291	270.233	155.173	270.004	292.495	262.135	151.778	269.876
-0.225	247.515	270.453	120.245	270.134	244.348	270.447	121.037	270.186
-0.15	147.786	269.698	67.523	270.050	146.583	269.559	68.937	269.875
-0.075	64.065	268.336	28.574	268.413	64.185	268.349	29.415	269.757
0	0.554	132.446	0.207	180.013	1.103	139.106	0.253	169.169
0.075	39.738	270.949	68.245	270.131	35.094	270.604	55.008	270.088
0.15	39.268	270.873	97.123	269.836	33.212	269.873	82.906	269.967
0.225	8.033	266.537	101.676	271.121	5.288	264.093	93.038	270.840
0.3	1.823	22.059	105.996	270.002	4.548	280.075	98.600	269.859
0.375	45.090	271.054	123.020	269.804	52.643	261.139	118.190	269.704
0.45	98.862	270.769	142.439	270.859	99.446	270.159	138.269	269.848
0.525	153.412	269.816	160.584	269.001	150.652	269.810	156.162	270.052
0.6	214.014	270.598	179.952	270.201	208.984	270.042	174.538	270.132
0.675	270.689	269.592	193.136	270.054	273.207	268.592	190.594	269.823
0.75	297.235	270.026	185.871	269.624	291.805	270.028	182.041	269.887

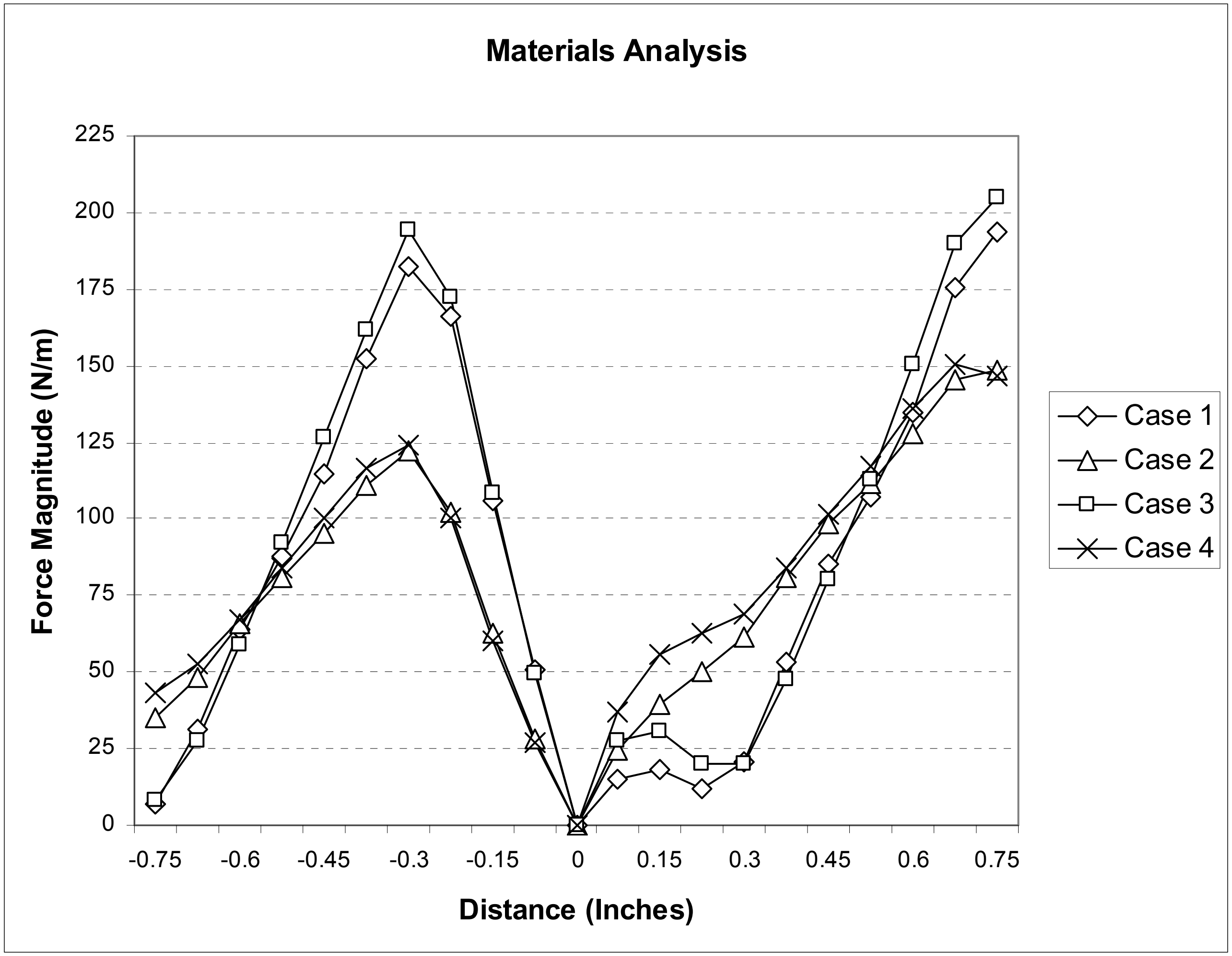


Figure 3.16. Force Magnitude Cases 1, 2, 3, 4.

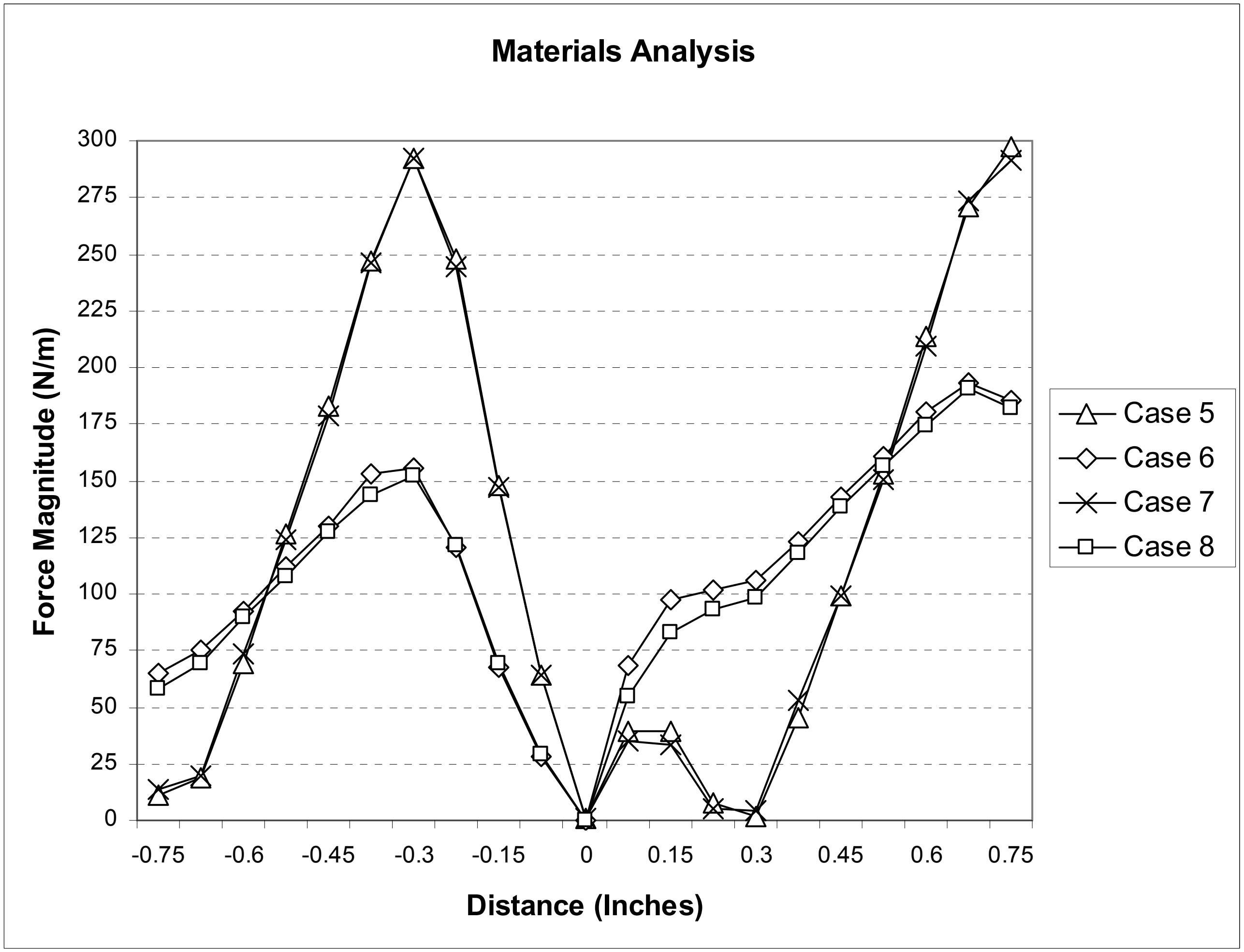


Figure 3.17. Force Magnitude for Cases 5, 6, 7, 8

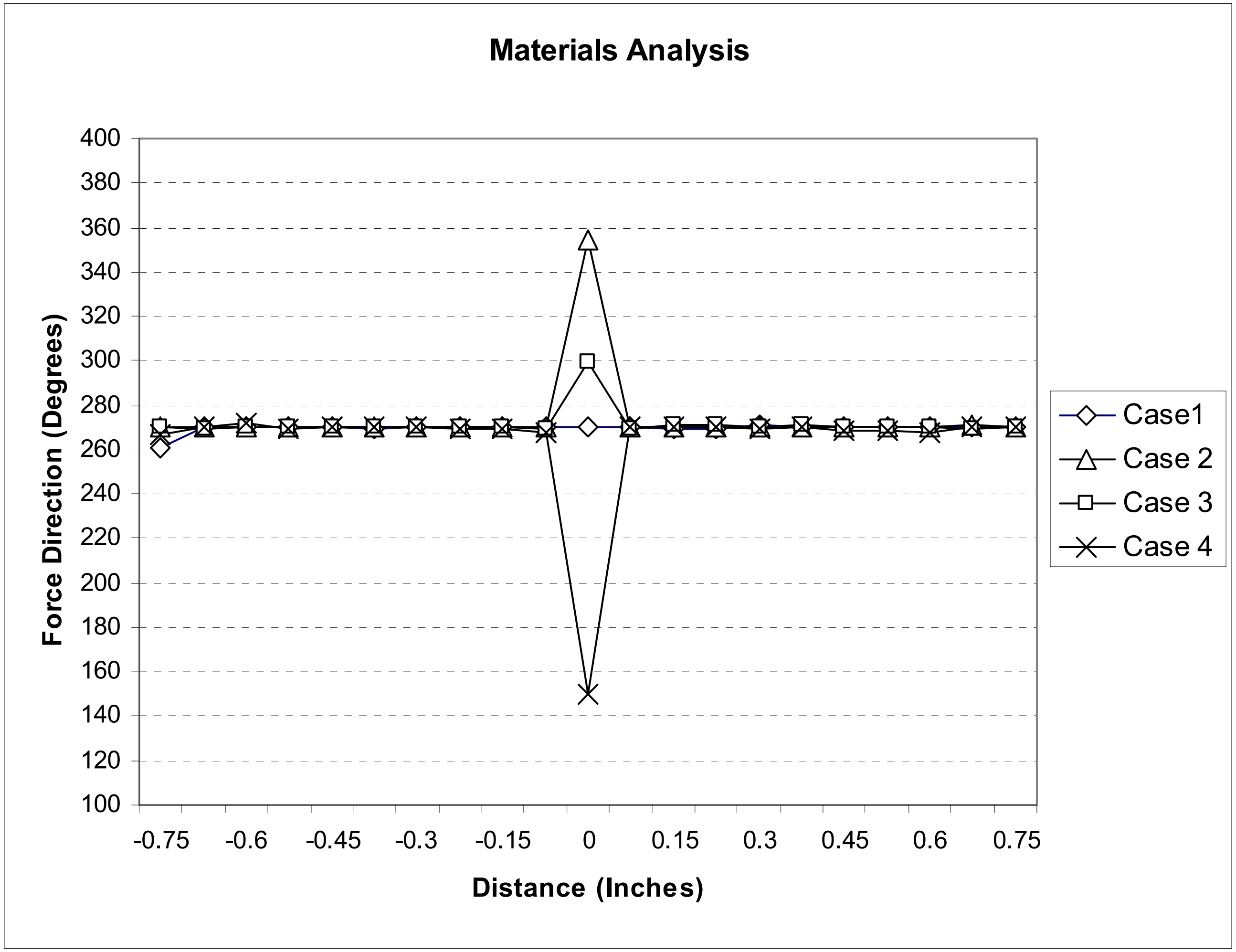


Figure 3.18. Force Direction for Cases 1, 2, 3, 4

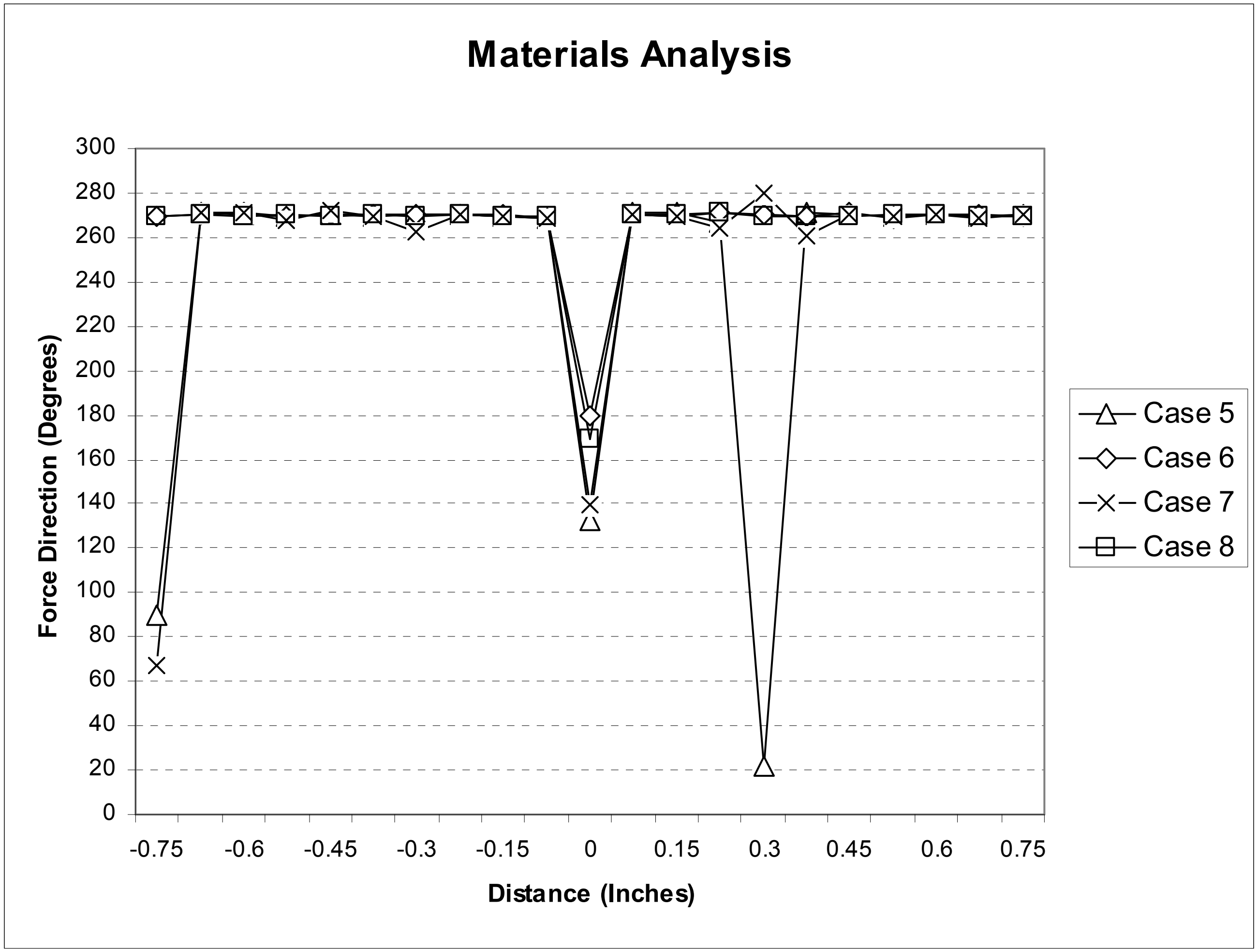


Figure 3.19. Force Direction for Cases 5, 6, 7, 8

In Figures 3.16 and 3.17 the effect of a change of materials in the force is mainly in magnitude as was expected. This as was mentioned before is due to the material characteristics. In the Figure 3.16 in general terms a similar tendency in all the cases it is observed. Again in the point 0 there is a force equilibrium because each tee is attracting the windingcore and each copper bar presents the same force but in opposite direction. Regarding the direction in Figure 3.18 there is a common tendency in all the cases except in the zero point but the force magnitude in this point is almost zero. This common tendency implies movement without abrupt changes. In Figure 3.19 some abrupt changes besides the changes in 0 point can be seen for the cases 5 and 7 but again, the force magnitude for this cases is almost zero.

Observing the Figures 3.16, 3.17, 3.18 and 3.19 the magnitude of the force is mainly affected by the materials characteristics and the direction of the force is in general terms affected by the current polarization however some points present abrupt changes in direction as in Figure 3.19.

The tendency in magnitude for the cases 2 and 4 in Figure 3.16 is very similar to the tendency of cases 6 and 8 in Figure 3.17. The same can be said for the cases 1 and 3 and the cases 5 and 7. This similarity is confirmed in Figures 3.20 and 3.21, 3.22 and 3.23.

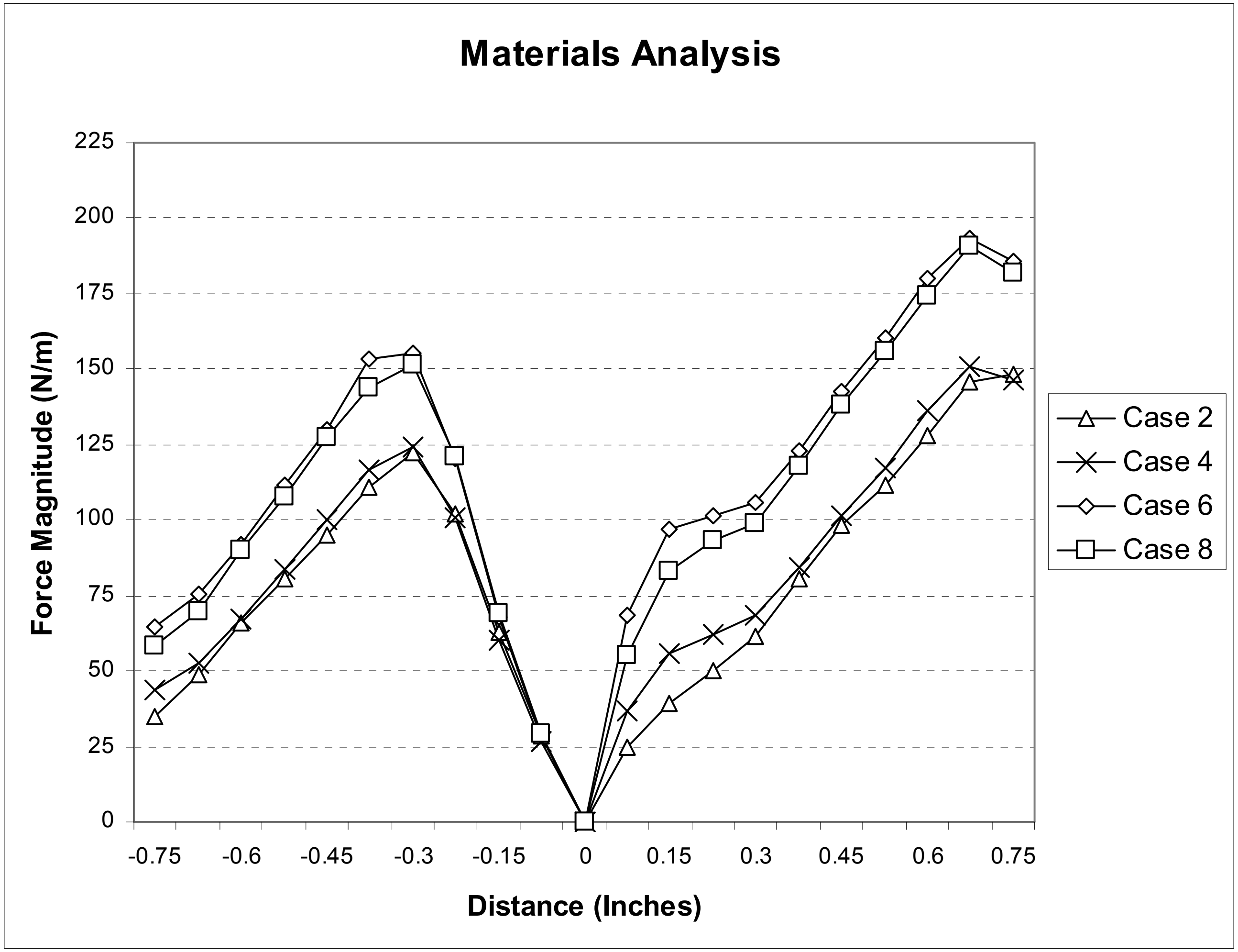


Figure 3.20. Force Magnitude for Cases 2, 4, 6, 8

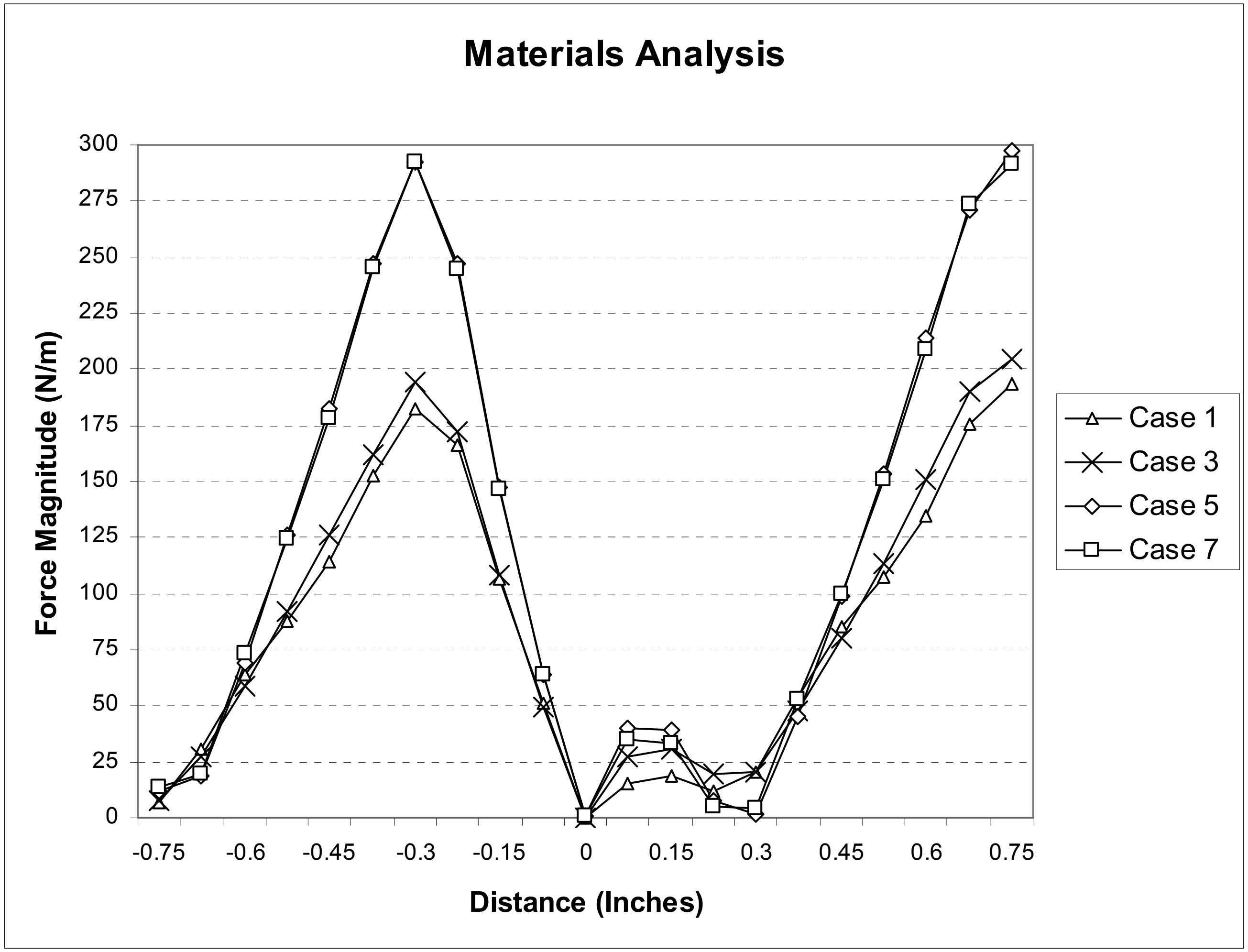


Figure 3.21. Force Magnitude for Cases 1, 3, 5, 7

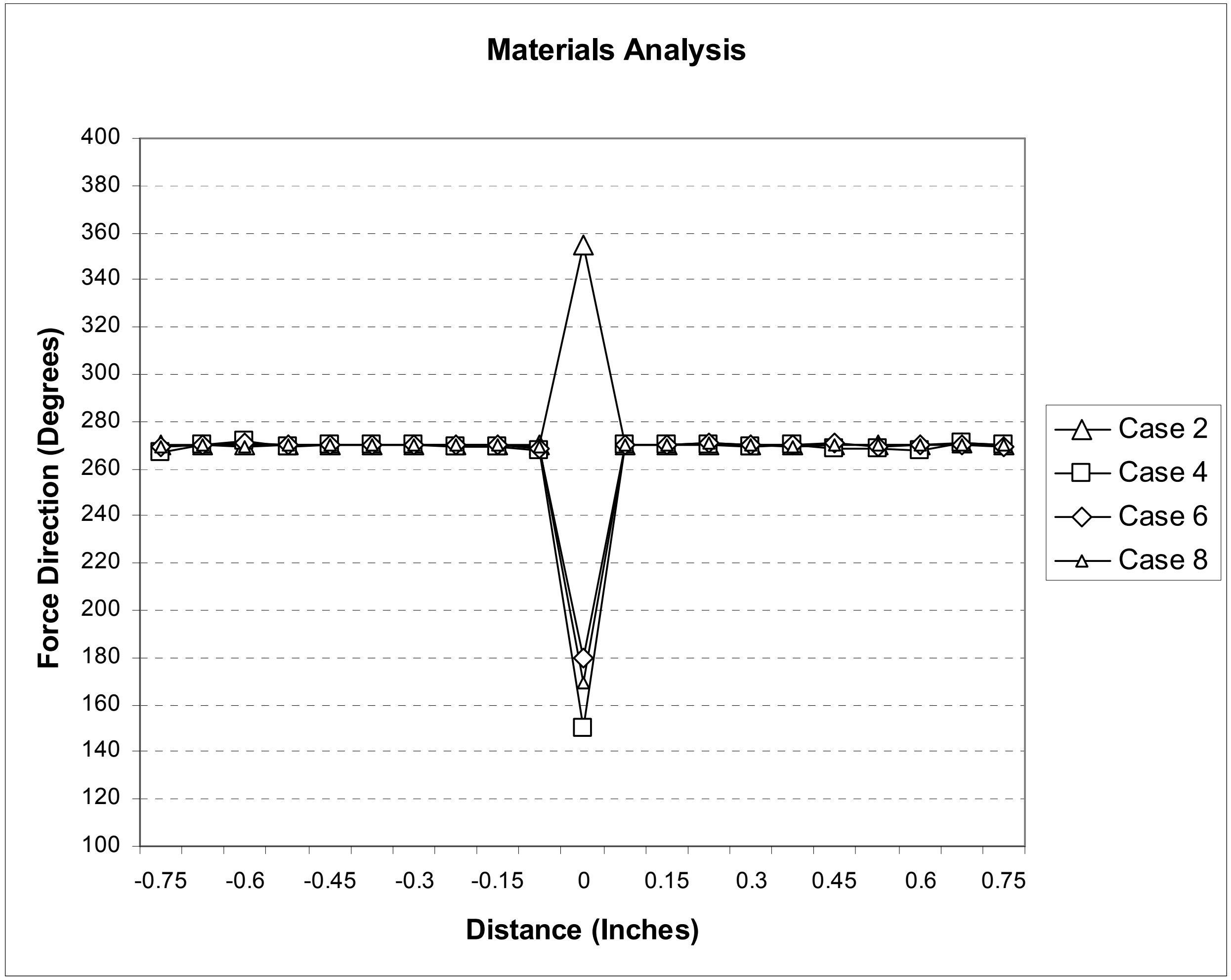


Figure 3.22. Force Direction for Cases 2, 4, 6, 8

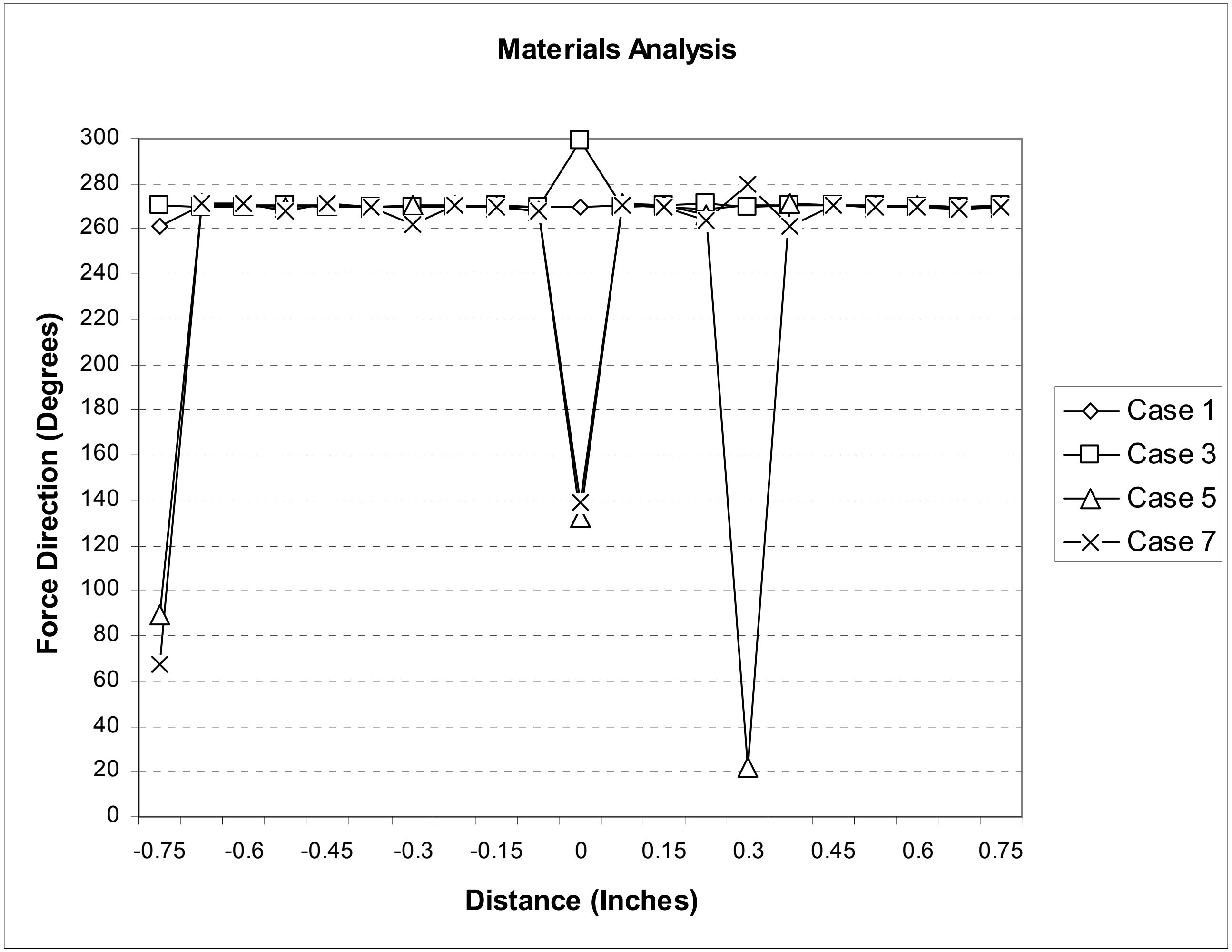


Figure 3.23. Force Direction for Cases 1, 3, 5, 7

Regarding Figure 3.20 the cases 6 and 8 present a larger magnitude for all the points, this is because of the characteristics of the materials, in Table 3.10 the materials for theses cases are shown

Table 3.10. Materials for the Cases 2, 4, 6 and 8

	Material			
Component	**Case 2**	**Case 4**	**Case 6**	**Case 8**
Tee	Cast Iron	Cast Iron	Iron	Iron
Windingcore	Cast Iron	Cold Rolled Steel	Iron	Cold Rolled Steel
Permanent Magnet	Alnico 5	Alnico 5	Alnico 5	Alnico 5

From Table 3.10 can be seen that the permanent magnets for all the cases are made of Alnico 5, however for the cases 4 and 8 the only difference is in the material of the tee’s but in Figure 3.20 a difference in magnitude is observed this is because for the case 8 the tee’s material is iron which generates a better concentration of the flux lines and an increment in magnetic field can be expected and therefore force magnitude is incremented. The relative permeability of the iron used in the simulations is 4000. For the cases 2 and 6 the force magnitude of case 6 is larger because the iron generates a better concentration of flux lines which implies an increment in magnetic field and force magnitude. From Figure 3.20 the cases 6 and 8 present a force magnitude very similar however the iron in the windingcore presents a better flux concentration for the case 6 and this represents the slight difference in Figure 3.20.

Table 3.11. Materials for the Cases 1, 3, 5 and 7

	Material			
Component	**Case 1**	**Case 3**	**case 5**	**Case 7**
Tee	Cast Iron	Cast Iron	Iron	Iron
Windingcore	Cast Iron	Cold Rolled Steel	Iron	Cold Rolled Steel
Permanent Magnet	Ceramic 5	Ceramic 5	Ceramic 5	Ceramic 5

In Table 3.11 the materials for the cases 1, 3, 5 and 7 are presented and for the exactly the same reasons the force magnitude of case 7 is bigger than the force magnitude of case 3. The same for cases 1 and 5. regarding Figure 3.23 for the case 5 the force direction presents an abrupt change but the force magnitude for this case is almost zero as can be seen in Figure 3.21

From Figures 3.20 and 3.21 the cases 1, 3, 5 and 7 present in general terms a bigger force magnitude than the cases 2, 4, 6 and 8 this difference in force is associated with the ceramic 5 of permanent magnets for the cases 1, 3, 5, and 7. From Figure 3.21 the magnitude for the cases 5 and 7 is almost the same and the only difference in material is the cold rolled steel in the windingcore for the case 7.

Chapter 4

Conclusions and Recommendations

After the simulation and analysis of Berdut design some facts can be concluded:

— Permanent magnets are a natural source of magnetic field, this means that the field cannot be controlled but can be redirected and concentrated by interlacing tee's. The concentration implies an increment of magnetic field without the necessity of changing the permanent magnets. This means that permanent magnets that present a low B_r as ceramic 5 can be used and the costs will be reduced.

— The tee's are responsible for the concentration and redirection and this property creates the uniform zones and reduces the bending zones. The size of the uniform zones is directly related with the size of the faces. Selecting materials with high relative permeability a better concentration can be reached and the magnetic field will be incremented. A recommended material for the tee's and windingcore is iron because this material presents a high relative permeability at a low cost. The recommended material for the permanent magnet is ceramic 5 due to the good performance for reaching the largest force magnitudes at a low cost.

— The polarization current is controlled in the winding and this controls the force direction. A control for the current polarization is recommended in order to control the force direction. The magnitude of the force can be increment by the characteristics of the materials but controlling the current magnitude the force magnitude can be controlled in a more precise way. In order to guarantee a stable and continuous movement control of the force magnitude is a must.

- When the dimensions of some permanent magnets in two Halbach array are modified and these are placed in such a way that they emulate the Berdut design uniform and bending zones are also created. The uniform zones size is directly related with the permanent magnets size. With permanent magnets of the same size the uniform zones size and the bending zones size are the same (Figure 2.30). When the permanent magnets associated with the uniform zones are reduced the uniform zones are also reduced but the bending zones remain the same because the permanent magnets associated with them remain the same (Figure 2.28). Simultaneously to the reduction in the uniform zones a better concentration of the flux lines is generated and as consequence the magnetic field magnitude is incremented (see Figure 2.28). The increment of the magnetic field in practical terms is not an advantage because it is associated with a smaller uniform zone and a small uniform zone is not useful for propulsion.

- The concentration zones and the bending zones of Figure 2.30 have an equal size due to the equal size of the permanent magnets. Comparing the configurations of Figures 2.29 and 2.30 the concentration zones in Figure 2.30 are bigger than the concentration zones of Figure 2.29 due to the magnetic characteristics of the two Halbach arrays and the bigger size of the permanent magnets compared with the size of the tee faces of Figure 2.29. From Table 2.13 the magnetic field in the concentration zones of Figure 2.30 is larger than the one in the concentration zones of Figure 2.29 indicating a better flux lines concentration but with bigger bending zones the configuration of Figure 2.30 will represent a more difficult alternative for a continuous movement.

A dynamic analysis is fundamental because factors like velocity, mass, and acceleration are involved in it and with this analysis a detailed exploration of the characteristics, total capacity and feasibility of Berdut design will be obtained and a justification for the implementation of a big scale model can be validated. With a scale model test results can be obtained and with the costs involved in such implementation a refined idea of the costs and benefices of a train based on Berdut design can be added to the feasibility study. The dynamic analysis can also discover the possibilities of the Berdut design in some others machines like elevators, cargo transport systems in ports or airports and amusement parks.

The movement of the train must be as smooth as possible and the necessity of a control system is valid in order to guarantee comfort and safety. The control system must meet this requirement and also must be responsible for the current polarization changes. These requirements impact directly the complexity of the control system.

Taking advantage of the movement in some portions of the railway the windings can be deactivated and by the relative movement between the windings and the magnetic field of the configuration current induction can be achieved. This current can be used as a redundant power system.

Reduction of the bending zones of configuration in Figure 2.30 could represent a new worthy alternative for a new linear motor based on Halbach array and Berdut design.

Appendix 1

Background of Permanent Magnets

In order to give a general background of all components and their role in the geometric configuration is important to deal with permanent magnet theory. Cost issues will be analyzed too.

The important role of permanent magnets in today's technology has been impulsed by the increment in applications associated to them in many fields of science. Thanks to the improvement of material properties the permanent magnets are more reliable and their properties are better understood [21]. The methods of measurement and calculation and also the processes of magnetization and stabilization have been improved. Nowadays the technical information about permanent magnets is very useful and wide spread [21]. As a consequence it is easier to select the materials for a given application. Permanent magnets have been in electrical machinery for over 100 years and cost and size have been reduced. Also the availability and performance of magnetic materials have been highly improved. With all this magnet applications in industry, science and consumer goods have been growing in direct relation. Nowadays it is very common to find miniaturized magnets in watches and electronic measurement equipment, other magnets are generally found in speakers, weighing systems, microwave ovens, small motors, automotive ignition and starters, cameras, video recorders, telephones, magnetically levitated vehicles and so on [21].

A permanent magnet is a device of magnetic material magnetized by an external magnetic field. Once magnetized permanent magnets retain a large magnetic moment after the magnetizing force has been removed. The permanent magnet can be seen as a magnetic field source that is able to interact with other permanent magnets or with electric currents. A technologically useful magnet must retain its magnetization in spite of the opposite field presence, high and cold temperatures and its magnetic properties must be stable in time and rough environments [21].

A1.1. Magnetic Permeability and Susceptibility

Magnetic permeability, μ, is defined as a proportionality constant such that:

$$\vec{B} = \mu_o(\vec{H} + \vec{M}) \qquad (1)$$

Where: $\vec{B}$ is the magnetic flux density (units Tesla= Wb/m^2)

$\vec{H}$ is the magnetic field strength (units A/m)

$\vec{M}$ is the Magnetization vector (Units A/m)

Where Wb stands A for Amperes and m for meters.

Permeability is defined as a material property that describes or indicates the easy establishment of a magnetic flux in the component.

If the material is linear in field: $\vec{M} = \chi\vec{H}$ (2)

Where: χ is the magnetic susceptibility.

Then: $\vec{B} = \mu_o(\vec{H} + \vec{M}) = \mu_o\vec{H}(1+\chi)$

χ is a unitless and is function of the applied field and can be either negative or positive. Positives values imply that the induced magnetic field $\vec{M}$ (that is, the magnetic field produced by the material) is in the same direction of the inducing field $\vec{H}$. Negative values imply that the induced magnetic field is in the opposite direction of the inducing magnetic field.

If non linear: $\chi = \frac{\partial \vec{M}}{\partial \vec{H}}_{H \to 0}$

In cgs system permeability is:

$$\mu = 1 + 4\pi\chi \qquad (3)$$

In mks system permeability is:

$$\mu = \mu_0 (1 + \chi) \qquad (4)$$

where μ_0 is the permeability of free space and has a value of:

$$\mu_0 = 4\pi\, x 10^{-7} = 1.2566\, x 10^{-6} \;\; H\, m^{-1}$$

Relative Permeability is defined as:

$$\mu_r = \frac{\mu}{\mu_0} = 1 + \chi \qquad (5)$$

A1.2. Types of Magnetism

Any material or substance can be classified according its magnetic behavior in five categories:

1. Diamagnetic.
2. Paramagnetic.

3. Antiferromagnetic.
4. Ferromagnetic.
5. Ferrimagnetic.

Materials that fall into the first three categories present a weak magnetic behavior and are commonly known as nonmagnetic. Materials in the last two categories are characterized by a strong magnetic behavior.

A1.2.1. Diamagnetic Materials

These are materials that repel an external magnetic field. The orbital motion of electrons in these materials generates magnetic fields. When an external field is applied to these materials the current loops created by the rotation of the electrons are aligned in such way that they oppose the external magnetic field. As a result there is a rejection of the external field. The relative permeability of a diamagnetic material is less than unity [30-31].

A1.2.2. Paramagnetic Materials

A paramagnetic material exhibits a magnetization proportional to the applied magnetic field. In these materials the molecular magnets (the smallest particles reached by means of division are called molecular magnets or domains), when an external magnetic field is applied, are aligned in the same direction of the external magnetic field but the thermal motion of the domains avoids a perfect alignment. If the external magnetic field is strong enough the paramagnetic materials becomes a magnet but this magnet exists only in the presence of the external magnetic field. When the magnetic field is removed the domains return to their random alignment. The relative permeability of a paramagnetic material is slightly greater than unity [30-31].

A1.2.3. Antiferromagnetic Materials

In this magnetic material the almost equal magnetic moments are lined up antiparallel to each other. The susceptibility increases as the temperature is raised until a critical temperature is reached, above this temperature the material becomes paramagnetic. The critical temperature is named Neel temperature [31].

A1.2.4. Ferromagnetic Materials

The magnetic moments are aligned parallel to external applied field. This creates a total field greater than the applied. Magnetic permeability of a ferromagnetic material is much greater than unity. Ferromagnetic materials have a critical temperature, called Curie temperature where they become paramagnetic. A ferromagnetic material exhibits the phenomena of hysteresis and saturation. These phenomena will be explained in section A1.3.1. Magnetic permeability depends on the magnetizing force [30-31].

A1.2.5. Ferrimagnetic Materials

The unequal magnetic moments remain line up antiparallel to each other. Permeabilities for these materials are similar to ferromagnetic material permeabilities. Magnetic characteristics of ferrimagnetic materials are almost the same characteristics as those for ferromagnetic materials [31]

A1.3. Permanent Magnet Basics

There are four classes of modern commercialized magnets based on their material composition, these classes are:

a. Neodymium Iron Boron (NdFeB).
b. Samarium Cobalt (SmCo).
c. Ceramic.
d. Alnico.

Neodymium Iron Boron and Samarium Cobalt are known as rare earth magnets because of its material components pertain to rare earth group of elements. The general composition of NdFeB is $Nd_2Fe_{14}B$ and SmCo has two compositions: Sm_1Co_5 often referred as SmCo 1:5 and Sm_2Co_{17} often referred as SmCo 2:17. NdFeB is the most recent addition in modern magnet materials and at room temperature exhibits the highest properties of all magnetic materials. Ceramic or Ferrite magnets have the lowest cost and are made of Barium (Ba), Iron (Fe) and Oxigen (O) or Strontium (Sr), Iron (Fe) and Oxigen (O). Their compositions are: $BaFe_2O_3$ or $SrFe_2O_3$. Alnico magnets have their name because of their composition Aluminium (Al) Nickel (Ni) and Cobalt (Co) [22, 26].

A1.3.1. The B-H Curve

The B-H also called hysteresis loop is the basis of magnet design. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, which is the condition presented when all elementary magnetic moments have become oriented in one direction [22], then the magnet material is demagnetized, saturated in the opposite direction and finally demagnetized again, all this under the presence and influence of an external magnetic field. The B-H curve represents the relationship between the flux density or magnetic induction, B in a permanent magnet and the magnetizing field strength or magnetic field intensity, H.

In CGS system flux density is measured in Maxwells (or lines) per square centimeter. One line per square centimeter equals one gauss. In the SI system flux density is measured in Tesla. One Tesla equals 10000 gauss. In CGS system magnetizing field strength is measured in Oersteds, in the SI system is measured in Ampere-turns per meter. $\frac{1000}{4\pi}$ A/m equals 1 Oersteds.

This process to produce the B-H curve can be seen in the following way:

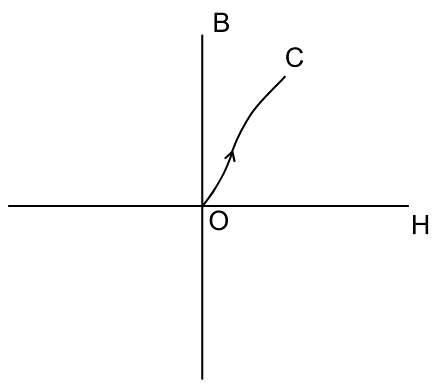


Figure 1. Hysteresis Loop. Saturation.

The point O in Figure 1 is the initial point, when there is no magnetization. Then the magnet is brought to saturation at point C by means of an external magnetic field H and the magnet no longer contributes to any increase in the flux density B. Any further increase in B is attributed to the relationship between the magnetizing field strength and the flux density of the space which is coincident with the magnet [23].

In Figure 2 the magnet is being demagnetized (portion CD) and the magnetization force H is being reduced to zero. Then the magnet is brought to saturation by demagnetization (portion DE) and magnetization (portion EF). This is reached by means of a negative direction increment of H. When H is zero the correspondent Value of B (point D) is called remanent flux density, remanence or retentivity and its symbol is B_r. When B is equal to zero the correspondent H value (point E) is known as a demagnetizing force called coercive force H_c. The point F expresses saturation in opposite direction.

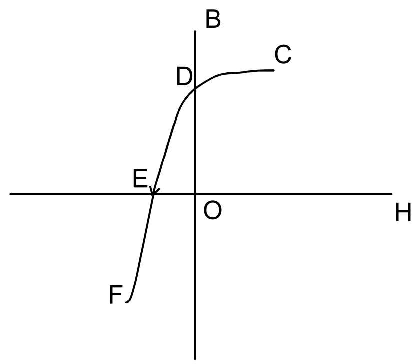


Figure 2. Hysteresis Loop. Demagnetization and Saturation in Opposite Direction.

In Figure 3 the magnet is being demagnetized (portion FG) and the magnetization force H is being reduced to zero in the reverse direction. The value of B when H is zero (point G) is $-B_r$. Then H is gradually increased and demagnetization continues until point I (portion FI) when begins the magnetization (portion IC) until saturation point C.

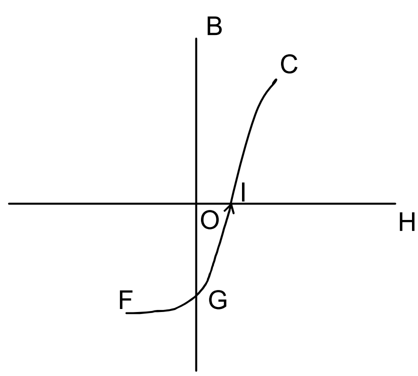


Figure 3. Hysteresis Loop. Demagnetization and Saturation.

The hysteresis loop is formed when Figures 1, 2 and 3 are merged:

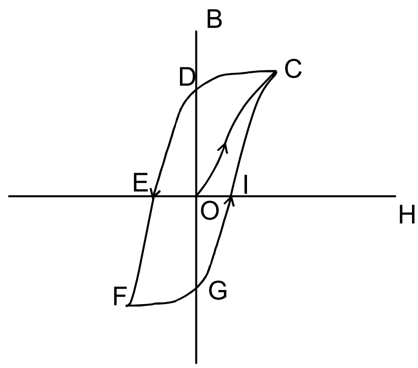


Figure .4. Hysteresis Loop.

Due to Hysteresis phenomenon initial demagnetization path CDE does not follow the saturation path OC in reverse direction.

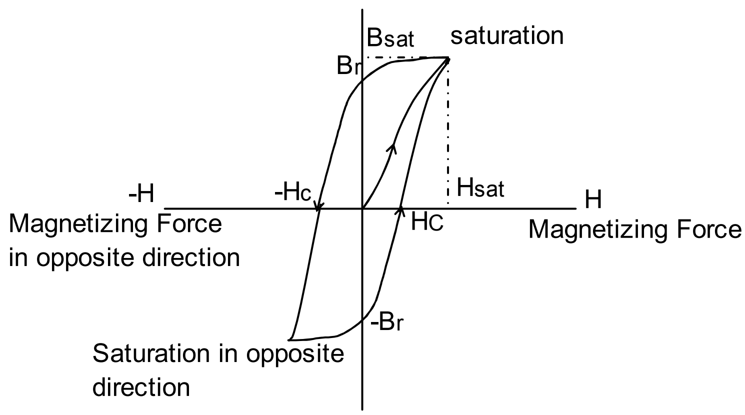


Figure 5. Characteristics of Hysteresis Loop.

Another hysteresis loop can be developed without bringing the magnet to saturation. This kind of loop is reduced in size with respect to its saturation counterpart. In this loop the value of B when H is equal to zero is known as residual magnetism or residual flux. Note that residual magnetism and retentivity (B_r) are the same when material has been magnetized to the saturation point.

A1.3.2. Permeability and B-H Curve

Equation 1 expresses the relationship between flux density and magnetizing force and describes the slope of the curve at any point on the hysteresis loop. In the hysteresis loop can be found many values of μ but in the catalogs or papers usually appears the maximum value of it, this is the point where the hysteresis loop has the greatest slope.

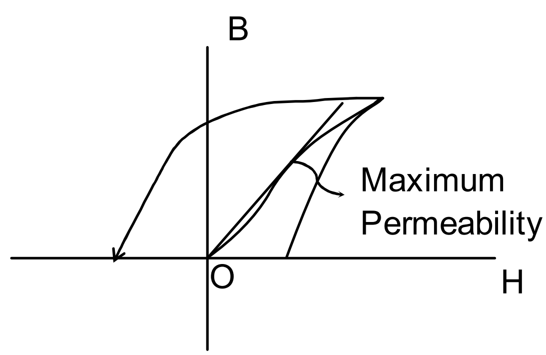


Figure 6. Maximum Permeability Point.

The second quadrant of Figure 5 is called demagnetization curve and describes the conditions under which permanent magnets are used in practice. The product of B and H at any point of demagnetization curve is called energy product.

A common figure of merit of a permanent magnet is the maximum energy product (BH_{max}) which is defined as the point on demagnetization curve where the product of B and H is a maximum and the energy density of the magnetic field into the air gap surrounding the magnet is also at its maximum. The higher this product, the smaller need be the volume of a magnet material required to generate a given energy into its surroundings [22].

A1.3.3. Construction of Hysteresis Loop

The construction of hysteresis loop is made possible using a magnetic closed circuit. One example of such a circuit can be seen in Figure 7.

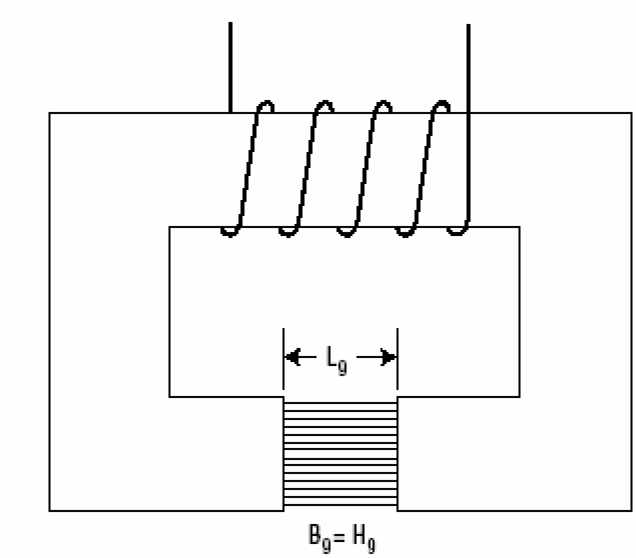


Figure 7. Circuit for Hysteresis Loop. [24]

Inserting a magnet sample between the poles of electromagnet of Figure 7 keeping the air gap between the poles and the magnet minimal the B-H curve can be generated. When an unmagnetized magnet is placed in the electromagnet and this is energized, a magnetizing field H is applied and the induction B will increase proportional to H (Figure 1), if H is reduced to zero then the portion CD of Figure 2 is generated. Reversing and gradually incrementing the current, the magnetizing force is reversed and the portion DEF of Figure 2 is generated. Reducing the current to zero the portion FG of Figure 3 is generated. Reversing, once again the current the portion GIC of Figure 3 is generated. In B-H curve the loop follows the measured B in the material and is called the normal curve.

However, from Figure 7 not all the observed flux is produced by the magnet because a flux is also produced in the air by the electromagnet. Flux density produced by the magnet itself is called intrinsic induction and is designated by B_i.

The flux produced in the gap by the electromagnet also can be drawn and with this curve and the normal curve another curve called intrinsic curve can be generated. The measured flux is equal to the sum of the flux which would be produced by the electromagnet without the magnet presence plus the flux produced by the magnet itself. The intrinsic curve is used when the magnet in an application is under the influence of an external magnetic field. The normal curve is used when is important to determine the amount of flux a magnet is capable of produced. From equation 6 the normal curve has a greater area than intrinsic one.

From Figure 2 at point D instead of reversing H the air gap is augmented demagnetization can also be achieved. This demagnetization must follow the portion DE of Figure 4 because the B-H curves are in general a plot of the magnet behavior. If the air gap is gradually augmented the flux density will decrease from B_r to any point in the portion DE of Figure 4. The flux is reduced because now the flux in the magnet is no passing straight through the magnet but the air gap is generating a leakage of flux. The flux leaking is returning to the opposite side of the magnet and because of the opposite direction this flux is a demagnetizing influence as shown in Figure 8.

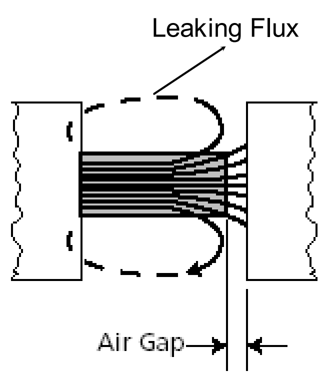


Figure 8. Leaking Flux. [24]

In an open circuit condition, when the magnet is extracted from the electromagnet, the flux density in the magnet will drop until a point that depends upon the geometry of the magnet. The geometry of the magnet can be equated to an operating slope (load line) or permeance coefficient: P_c=B/H.

If a permanent magnet is operating under an external demagnetizing field in an air gap the flux density will decrease.

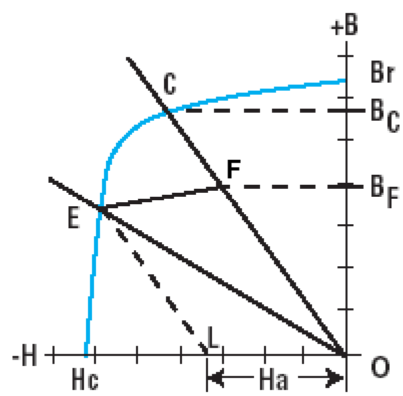


Figure 9. Effect of an External Field. [24]

In Figure 9 line OC represents the operating slope of a magnet in a circuit with some air gap, Bc represents the flux density in the magnet. When an external field of magnitude H_a is applied to the magnet, the flux will decreased to point E. When a magnet material has a knee shape demagnetization curve in case of canceling external demagnetization field H_a the flux density does not return to point C. The flux will return along a line with the slope of recoil permeability represented by EF. Note that when the external field is removed the flux returns to a point in the original line OC. The slope of line OFC is known as the recoil or reversible permeability of the magnet.

In materials whose demagnetization curve is a straight line suchs as Ceramic, Samarium Cobalt or Neodymium Iron Boron the flux loss is greatly reduced [24].

A1.3.4. Magnet Calculations

The following equations can be used in absence of any coil excitation [22]:

The objective of these equations is to find the length and pole area of the magnet given the gap flux density, the magnetization force at the operating point and the air gap length (Figure 8) The magnet length can be calculated as follows:

$$L_m = \frac{B_g L_g}{H_m} \qquad (6)$$

where: L_m = the magnet length,

B_g = the gap flux density,

H_m = the magnetizing force at the operating point,

L_g = the air gap length.

Pole Area:

$$A_m = \frac{B_g A_g}{B_m} \qquad (7)$$

where: A_m = the magnet pole area,

B_g = the gap flux density,

B_m = the flux density at the operating point,

A_g = the air gap area.

From 6 and 7:

$$P_c = \frac{B_m}{H_m} = \frac{A_g L_m}{A_m L_g} \quad (8)$$

P_c can be calculated in a more accurate way:

$$P_c = \frac{B_m}{H_m} = \mu \left(\frac{A_g L_m}{A_m L_g} \right) k \quad (9)$$

where: μ = permeability of the medium,

k = factor which takes account of leakage and reluctance that are functions of the geometry and composition of the magnetic circuit.

A1.3.4.1. Calculation of flux density

In the case of magnet materials with a straight line as a demagnetization curve (NdFeB, alnico and ceramic), it is possible to calculate the flux density at a distance x from the pole surface on the magnet center line under a variety of conditions. The magnets used in the Berdut train will be rectangular in shape; then the magnet flux equation is relevant:

$$B_x = \frac{B_r}{\pi} \left(\tan^{-1} \left(\frac{hd}{2x\sqrt{4x^2 + h^2 + d^2}} \right) - \tan^{-1} \left(\frac{hd}{2(L+x)\sqrt{4(L+x)^2 + A^2 + B^2}} \right) \right) \quad (10)$$

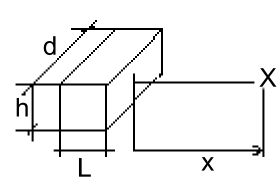


Figure 10. Geometry and Physical Dimensions [22].

The objective of an efficient magnet design must be to minimize as much as possible the volume of a magnet material. This is possible operating the magnet at the BH_{max} point.

A1.3.5. Stability

If a permanent magnet is divided into small particles, these particles would also have opposite poles north and south, the smallest particles reached by means of division are called molecular magnets or domains. All magnetic materials are made of molecular magnets. In a non magnetized condition all molecular magnets are randomly oriented and there is no net magnetic effect. In the magnetized condition, an external magnetic field forces the molecular magnets to be oriented in a specific direction and as a result the magnet is magnetized. Once established, the magnetization can be reversed by a force that exceeds the original magnetizing forces. The energy required to disturb the magnetic field produced by a magnet varies for each type of material. Permanent magnets can have high coercive forces and as a consequence they will maintain the molecular magnets aligned in the presence of high external magnetic fields. High and low temperatures, time, adverse fields, radiation, shock, stress and vibrations can affect the magnet stability.

Stabilization process is necessary because [23]:

- It reduces the effects of thermal changes on operation.
- It protects magnets against irreversible reduction in performance due to the presence of demagnetization fields.
- It calibrates magnets for precise performance.

The stabilization process implies a reduction in performance by partial demagnetization. The application of demagnetization field will cause a shift along demagnetization curve. In Figure 11 the demagnetization field causes a movement in the operation point from B_3H_3 (permeance line OP_1) to B_1H_1 (permeance line OP_2). Once demagnetizing field is removed, the operating point goes to B_2H_2. The effect of this process is that within the range $H_2 - H_1$, the magnet operation is reversible. The application of a lesser external field will not cause a permanent reduction in magnet performance since any variation in the range $H_2 - H_1$ results in a magnet flux density change according to the minor loop MN [23]. Magnets used in measurement equipment receive this treatment in order to guarantee protection against the incidence of stray fields. The removal of stray field re-establishes the original calibration.

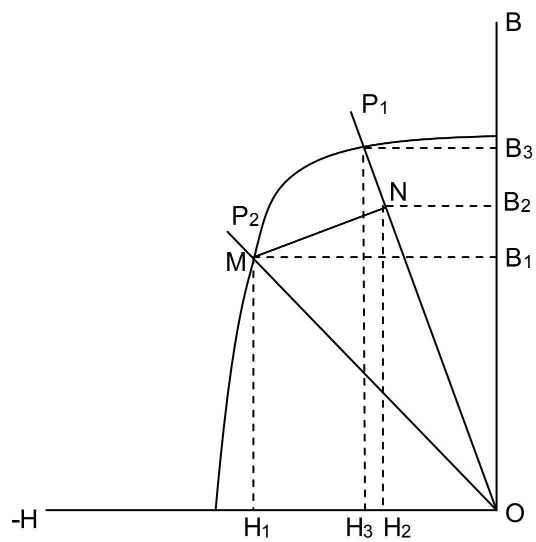


Figure 11. Stability Process [23].

A1.3.5.1. Time

In permanent magnets there is an amount of molecular magnets that are less stable; these domains are affected by variations in temperature or magnetic energy, even in a thermally stable environment. In modern magnets the effect of time is minimal and this effect occurs mostly immediately after magnetization. The changes occur when the less stable molecular magnets are affected. The lesser unstable molecular magnets the lesser time effect. The time effect is not possible in rare earth magnets due to the high coercivities. Some studies have shown that without external flux after 100,000 hours, the losses in flux are about zero for Samarium Cobalt and less than 3% for Alnico 5 at low permeance coefficients [22].

A1.3.5.2. Temperature

Temperature effects can be classified into three categories:

- Reversible Losses.
- Irreversible but recoverable losses.
- Irreversible and unrecoverable losses.

A1.3.5.2.1. Reversible Losses

When a magnet is in a high temperature environment there are changes in flux that can be reversible when the magnet is returned to its original temperature. These losses are called reversible losses and can be described by the reversible temperature coefficients (T_c). There are two values, reported reversible temperature coefficient of inductance (B_r) and reversible temperature coefficient of coercivity (H_c). These coefficients are usually expressed as percentage of change per unit of temperature.

Table 1. Reversible Temperature Coefficients of B_r and H_c. [22]

Material	T_C of B_r	T_c of H_c
Neodymium Iron Boron	-0.12	-0.6
Samarium Cobalt	-0.04	-0.3
Alnico	-0.02	0.01
Ceramic	-0.2	0.3

A1.3.5.2.2. Irreversible but Recoverable Losses

These losses are not recoverable when the magnet is exposed to high or low temperature and then returned to its original temperature. They are only recoverable by remagnetization. These losses occur when the operating point is located bellow the “knee” of demagnetization curve. In order to avoid these losses the magnet has to be operated at a permeance coefficient above the knee at expected working temperatures.

A1.3.5.2.3. Irreversible and Unrecoverable Losses

These losses occur when the magnet is exposed to high temperatures and they are associated with metallurgical changes in the magnet. These losses are not recoverable by remagnetization. There are two critical temperatures:

- T_{Curie} at this temperature the domains are randomized and the magnet losses its magnetism.

- T_{max} is the maximum temperature to which the magnet can be exposed with no significant long-range temperature instability or structural changes. Different grades of materials can cause a slightly shift in T_{max}.

Table 2. Critical Temperatures. [22]

Material	T_{Curie} [Degree Centigrade] (Fahrenheit)	T_{max} [Degree Centigrade] (Fahrenheit)
Neodymium Iron Boron	310 (590)	150 (302)
Samarium Cobalt	750 (1382)	300 (572)
Alnico	860 (1580)	540 (1004)
Ceramic	460 (860)	300 (572)

A1.3.5.3. Reluctance Changes

Reluctance is an analog of electric resistance and is related to magnetomotive force, F and the magnetic flux ϕ by the equation:

$$R = \frac{F}{\phi} \qquad (11)$$

A magnet is designed to overcome the reluctance of the magnetic circuit by means of determining its dimensions as well as materials. The magnetomotive force produced by the magnet must overcome the reluctance of the circuit and produce the desired flux. When a magnet is subject to changes in the air gap the reluctance of the circuit can vary and the operating point can be shifted bellow the knee where irreversible losses are generated. These changes depend upon the material properties and the extent of the permeance change [22].

A1.3.5.4. Adverse Fields

When a magnet is under the influence of an external field with opposite direction of the magnet polarization demagnetization occurs. Magnets with high coercive force such as rare earth magnets are almost unaffected but magnets such as alnico 5 with a coercive force of 640 Oe can present demagnetization in presence of an adverse field. Ceramic magnets with coercive force of 4 KOe should be carefully evaluated in order to know the effect of external magnetic fields [22].For the case of Berdut design ceramic 5 and alnico 5 permanent magnets were used. These permanent magnets are not under adverse fields because the magnetic field generated by the windings is mainly concentrated in the windingcore.

A1.3.5.5. Radiation

Permanent magnets are used in applications that involve a radiation environment such as deflection beams applications or accurate measurement equipment. For this reason is necessary to evaluate radiation effects in magnets. Studies have shown that Samarium Cobalt magnet withstand radiation 2 to 40 times better than NdFeB materials. In general, it is recommended that magnet materials with high H_{ci} values be used in radiation environments that they can be operated at high permeance coefficients, P_c, and they must be shielded from direct heavy particle irradiation [22]. Stabilization can be achieved by pre-exposure to expected radiation levels.

A1.3.5.6. Shocks, Stress and Vibration

Some magnetic materials are by nature fragile, so these materials must be manipulated with care. In general, vibration, stress and shocks nowadays are not a problem with modern magnets but as solid materials they cannot be exposed to destructive environments. A common way of protection is surface coating. The need of coating depends on the work environment of the permanent magnet. In some applications is necessary the protection against corrosive materials, acids, alkaline solutions etc. The coating depends on the application itself.

A1.3.5.7 Safety and Costs

The attraction caused by permanent magnets in magnetic materials can be dangerous when the magnetic field is strong. In order to avoid damage in the magnet or in persons careful is a must. Sometimes a shield must be installed in order to protect people from high magnetic fields. NdFeB and SmCo are the alloys that produce the highest magnetic energy and allow minimum physical dimensions. These characteristics are reflected in their price, performance and consume demand. In the Figure 12 a comparison of prices for different permanent magnets is shown.

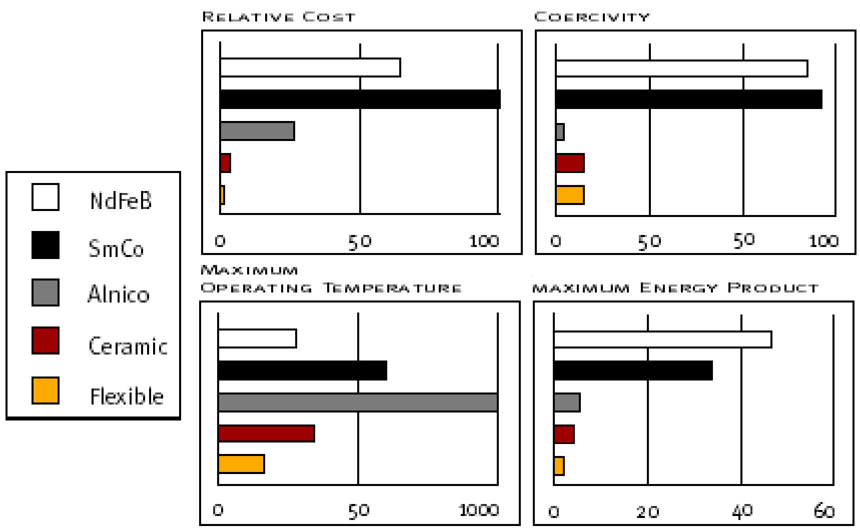


Figure 12. Comparison of Permanent Magnets Costs. [22]

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