# BRUSHLESS DC MOTOR PHASE, POLE AND SLOT CONFIGURATIONS

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## ABSTRACT

DC Motors with the Permanent Magnets contained in the rotor rather than the stator do not require brushless or a mechanical commutator. These characteristics of the Brushless DC Motor (or AC Servo as sometimes is used) makes them one of the most popular motors in the world today.

Many technical articles and papers have been written on the design of Brushless DC Motors including magnetic simulation analysis using the FEM or BEM computer solvers. The controversy surrounding Sinusoidal vs. Trapesordal Drives has also prompted much technical analysis including "Phase Plane" analysis.

However before a brushless motor design can commence, several basic decisions must be made.

- NUMBER OF PHASES
- NUMBER OF POLES
- NUMBER OF STATOR SLOTS
- WINDING PATTERN

With few exceptions it appears that the above very important selections are taken for granted and the full scope of possibilities and performance vs cost trade offs are seldom pondered and analyzed.

The purpose of this paper is to analyze the selection of the number of phases, rotor poles and stator slots so that selections can be made before the actual motor design is attempted. The analysis and comparisons are performed using computer simulation software with the following variables.

- NUMBER OF PHASES
- NUMBER OF POLES
- NUMBER OF SLOTS

Selecting any two of the three as independent variables allows computation of all of the possible values of the remaining variable.

Finally another program is used to calculate and plot the actual back EMF of each simulated design. This is done by selection a magnet pole arc, number of slots, number of phases and the number of poles, then the model simulates the back EMF of that configuration.

This analysis is independent of motor size, voltage, windings, lamination design or magnet grade. However, a graphic picture of back EMF ripple is clear, and the magnet arc can be optimized as well as a determination of the performance cost trade offs.

## I INTRODUCTION

The generally accepted definition of a Brushless DC Motor would include a description of the stationery part of the motor as consisting of a stack or lamination pack containing copper windings or coils arranged in a certain pattern. The rotating portion of the Brushless DC Motor would consist of some Permanent Magnets imbedded in iron laminations on the shaft or cemented to the outside diameter of the laminated rotor. When the stator windings are properly connected to a DC or AC power source the electro magnetic flux generated in the stator iron cross links the Permanent Magnet flux from the rotor and the resulting torque causes shaft rotation.

Figure 1-A shows a (2) phase uni-polar design which is very common for small low cost fans. Figure 1-B depicks a (3) phase (4) pole, (6) slot brushless motor with the coils wound around a single stator tooth the same as Figure 1-A. Figure 1-C is an (8) pole, (18) slot motor with (3) phases and a (2) slot coil winding pitch. Figure 1-D is a common brushless configuration for (3) phase motors with (4) poles, (12) slots and a (3) slot coil winding pitch. Figures 1-E and 1-F are brushless designs with (6) pole imbedded rotor magnets. Figure 1-E represents a (4) phase motor with (12) slots and a (2) slot coil winding pitch. Figure 1-E is a (3) phase motor with (18) slots and a (3) slot coil winding pitch.

Usually before a brushless motor design can commence, the designer must evaluate the requirements, functions, and purpose of the motor to be designed. When a general grasp of its purpose is defined, the next step consists of establishing certain conditions before the design can begin. For example the following list must be decided upon.

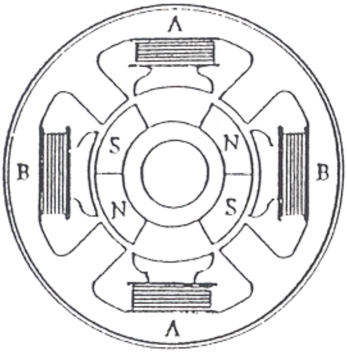



FIGURE 1-A

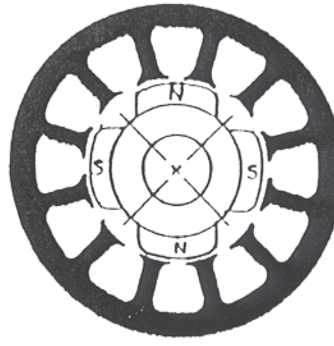



FIGURE 1-D

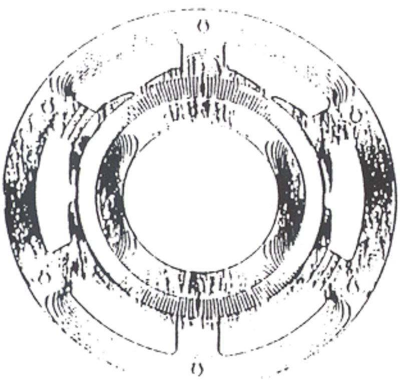


FIGURE 1-B

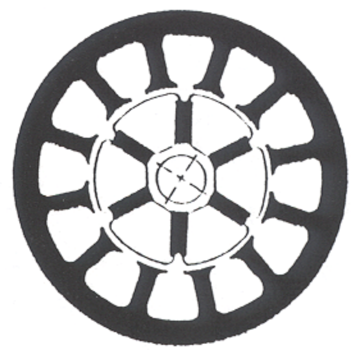


FIGURE 1-E


FIGURE 1-C

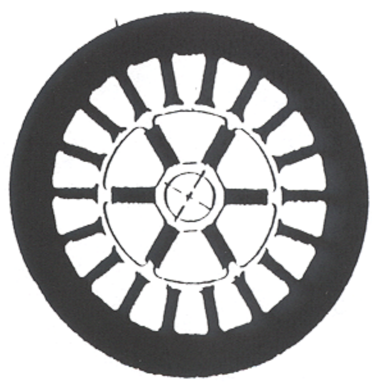


FIGURE 1-F

- NUMBER OF PHASES
- NUMBER OF ROTOR POLES
- NUMBER OF STATOR SLOTS
- WINDING PATTERN AND CONNECTIONS
- ELECTRONIC COMMUTATION METHOD
- SINE DRIVE OR TRAPEZOIDAL DRIVE

It is not the intent of this paper to consider the entirety of the above list with respect to a Brushless DC Motor design analysis. Each experienced Brushless DC Motor designer can well enough decide upon the correct choice of magnet materials, conventional rotor or inside out rotor and even the commutation scheme required for his or her application requirements. In fact the intended purpose of this analysis is to provide a brief study concerning the choice of the number of phases and most importantly a fairly detailed (although not at all complete) analysis of the number of rotor poles and some of the possible winding patterns and slot configurations.

Most of the Brushless DC Motors currently in use are quite conventional in terms of the number of poles and winding arrangements. Much of what is being offered has its beginnings from AC induction motors. In fact many designs are AC Motors with a special Permanent Magnet rotor replacing the die cast squirrel cage rotor. There are up front economic reasons for approaching a Brushless DC Motor by utilizing an existing production line with full manufacturing tooling and machinery, but the brushless motor that results from those situations are hardly optimized and most likely doomed to limited success in the market place when compared to an optimized Brushless DC Motor design.

Presented here is a study of some of the different pole and slot winding configurations possible for Brushless DC Motors. Some of the trade offs are given to enable the designer to select the best choice at the outset of his or her design. Knowing what the possibilities are enables the designer to perform some comparative designs using different arrangements and analyzing the trade offs.

## II NUMBER OF PHASES

When a Brushless DC Motor operates at very low speeds (under 100 RPM) the actual torque developed as the motor rotor rotates has the same variable content as the voltage generated (or BACK EMF). There are many techniques used to minimize this variation because it contributes to torque ripple and but will not be discussed in this paper. In an effort to select a number of phases with a corresponding 2 x number of switching transistors the fundamental torque ripple as a percent of the peak value should be analyzed.

Table 1 shows most of the important comparative data for several different phase choices. The torque ripple percentages are based upon sinusoidal Back EMF at low speeds. The percentage of the effective conductors relates to the output power vs the motor volume because of the total space used for copper conductors only a portion of those conductors carry current to produce torque because the phases are switched on and off. This is true of WYE connected phases but the delta connections result in a similar ratio based upon the number producing torque and the total number even though all conductors carry current.

**TABLE I**

| PHASE NUMBER | COND. % | COMM. SENSOR | POWER SWITCHES | TORQUE RIPPLE |
|---|---|---|---|---|
| 1 | 50% | 1 | 2 | 100% |
| 2 | 50% | 2 | 4 | 30% |
| 3 | 67% | 3 | 6 | 15% |
| 4 | 75% | 3 | 8 | 10% |
| 6 | 83% | 4 | 12 | 7% |
| 12 | 92% | 5 | 24 | 3% |

The only advantages to the (6) & (12) phase machines are the low torque ripple and the high utilization of copper which makes them similar to brush type DC Motors. However, the cost of power semiconductors and commutation sensor switched usually is far more undesirable than their advantages. Also the switching losses are significant at any reasonable speed with these high phase machines. The only reasonable application might be for a brushless DC torquer. The single phase configuration results in zero torque every 180 degrees so that a "trick" is required to assure starting and in the correct direction of rotation. The low cost of electronics however makes them attractive for some fan applications which have high inertia from the fan or blower wheel so that torque ripple is dampened out. Most brushless applications usually utilized (3) phase designs. This choice is the best choice considering the trade offs as shown in TABLE I.

## III NUMBER OF POLES

The number of poles selected by the motor designer is quite important and depends on many factors. There are some general considerations which can be listed as follows.

- Magnet Material and Grade
- Mechanical Assembly of Rotor
- Speed of the Rotor
- Inertia Requirements

For todays Brushless DC Motor there are not too many choices of magnet types but there are several grades with different properties of each type of magnet.

In the days when ALNICO magnets were the only choice, the magnet was designed to operate at it's maximum energy product. However, with the Rare Earth Magnets, it is not possible to do this because the mills can not make them thin enough. Figure (2) shows a consequent pole design which eliminates the extra cost of thicker magnets because only half the number of magnets are used. In general the lower the motor speed the greater the number of poles and the higher the speed the fewer number of poles are used. The actual rotor design can have an effect on the pole count selection. The magnets can be surface mounted, (Figure 3) imbedded in the rotor (Figure 4) or a radally oriented 360 degree ring magnet can be molded with the poles magnetized in place (Figure 5).

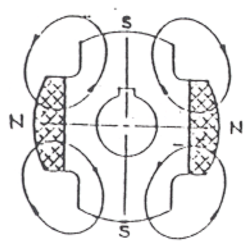



FIGURE 2

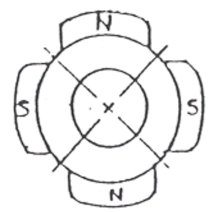



FIGURE 3


FIGURE 4

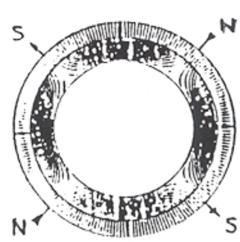



FIGURE 5

## IV TORQUE AND BACK EMF IN A BRUSHLESS DC MOTOR

Much has been written on how torque is produced in a BLDC motor using Faradays law, co-energy and flux linkages so very little will be repeated here. However, to consider the number of stator slots and phase coils that should be used with a certain number of poles, the analysis of the torque or rotor reacting torque from each conductor should be analyzed as its electro magnetic flux is cross linked with the permanent magnet flux of the rotor.

The Permanent Magnet pole arc length is very important and the uniformity of the flux density across the surface of the magnet has a great effect on the torque produced of one phase as the rotor rotates. Uniform flux across a pole is usually assumed but careful measurements in a closed soft iron circuit using a calibrated analog Hall sensor can reveal significant variations, particularly at the pole tips and magnets ends. This is usually not the case for the rare earth magnets which are pre-magnetized before assembly. However such magnets are ring magnets and various rotor and motor assemblies can be very difficult to saturate uniformly.

CAD and modeling techniques using a Fourier series to express the flux distribution in the air gap results in generating the motor Back EMF and Torque. A plot of the wave form is then outputted for one phase as a function of a rotor pole pair rotation. This can enable the designer to analyze many slot/winding configurations. Skewing of the rotor poles and stator slots can also be investigated. Such modeling methods save considerable cost and time with the added benefit of revealing some very useful and not so obvious slot/pole combinations.

## V STATOR SLOTS/WINDINGS

It is surprising that certain rotor pole, slot/winding and phase relationships seem to be quite popular. You would expect that most existing brushless motors use slot/pole choices that produce the best performance but as we will find using computer analysis, this is not always the case. For example most (3) phase (4) pole brushless motors are designed using (12) slot laminations with a (3) slot pitch distributed winding. This type of design has a very high reluctance cogging torque and very large end turns which contribute to I R losses. The winding is not simple to wind and very expensive machinery is required to keep the labor at a minimum. For a low cost and low cogging (4) pole motor, a (6) slot stator should be chosen. This is from the (1.5) slot/pole series of configurations. If a low cogging sinusoidal motor is desired, a (4) pole (15) slot lamination with a (4) slot winding pitch is the best all around choice from the (3.75) slot/pole series.

Most (8) pole motors use (24) slots but an (18) slot stator is superior. Another excellent low cost low cogging (8) pole design would be an (8) pole (9) slot motor. Both of these (8) pole motors produce near perfect sinusoidal torque at low speeds and very few rotor pole edges can align themselves with stator slot openings to produce cogging torque.

Table II shows a list of most of the possible pole/slot combinations for (3) phase bipolar driven (full wave) Brushless DC Motors. They are listed in groups according to the ratio of the number of slots per pole. The reason for this is that the Back EMF and torque shapes (at very low speeds) are the same for each number of poles in a group. For example the shape of a (4) pole (12) slot Back EMF is the same as the (6) pole (18) slot and the (8) pole (24) slot because they each belong to the group of (3) slots per pole.

What follows is an example from each of (6) of the (9) slot/pole groups from Table II using Fourier series analysis of this Back EMF (and torque at low speeds). This data was generated on a IBM PC AT computer and the results printed out for both DELTA and WYE connections, full pitch magnet arcs and 2/3 full pitch as well as straight stack and a one slot stator or rotor skew. As stated earlier, each group is represented by the example given and although these are normalized or without values they are independent of motor dimensions. I have personally built many of these configuration and the overall shapes are correct. The software does not take into account for stator slot openings which alters flux distribution and winding distributions. It also assumes no air gap so that the slopes are all too steep as compared with actual measured data. The point is that this method allows a rapid analysis of many combinations of slots and poles thereby allowing more choices for the designer in accordance with his motor requirements without actually building many different motors.

TABLE II

BLDC STATOR SLOT - POLE COMBINATION

FOR (3) PHASE MOTORS

.75

| Slots | Poles |
|---|---|
| 3 | 4 |
| 6 | 8 |
| 9 | 12 |
| 12 | 16 |
| 15 | 20 |
| 18 | 24 |
| 21 | 28 |
| 24 | 32 |

1.125

| Slots | Poles |
|---|---|
| 9 | 8 |
| 18 | 16 |
| 36 | 32 |

1.500

| Slots | Poles |
|---|---|
| 3 | 2 |
| 6 | 4 |
| 9 | 6 |
| 12 | 8 |
| 15 | 10 |
| 18 | 12 |
| 21 | 14 |
| 24 | 16 |

2.25

| Slots | Poles |
|---|---|
| 9 | 4 |
| 18 | 8 |
| 27 | 12 |

3.00

| Slots | Poles |
|---|---|
| 6 | 2 |
| 12 | 4 |
| 18 | 6 |
| 24 | 8 |
| 30 | 10 |
| 36 | 12 |

3.75

| Slots | Pole |
|---|---|
| 15 | 4 |
| 30 | 8 |
| 45 | 12 |

4.500

| Slots | Poles |
|---|---|
| 9 | 2 |
| 18 | 4 |
| 27 | 6 |
| 36 | 8 |

5.25

| Slots | Poles |
|---|---|
| 21 | 4 |
| 42 | 8 |

6

| Slots | Poles |
|---|---|
| 12 | 2 |
| 24 | 4 |
| 36 | 6 |
| 48 | 8 |

.750 SLOTS PER POLE

6/8

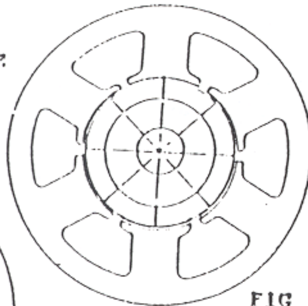


FIG 6-B

45° MAGNET

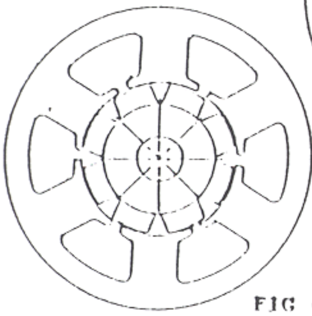


FIG 6-A

30° MAGNET

1.125 SLOTS PER POLE

9/8

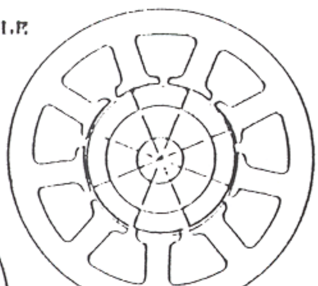


FIG 7-B

45° MAGNET

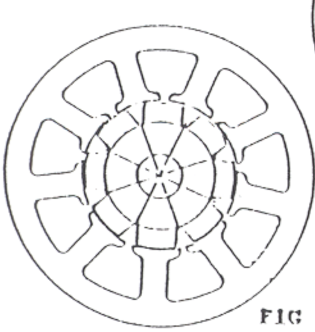


FIG 7-A

30° MAGNET

1.500 SLOTS PER POLE

6/4

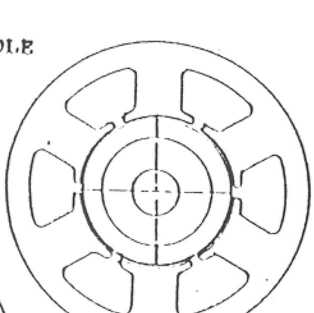


FIG 8-B

90° MAGNET

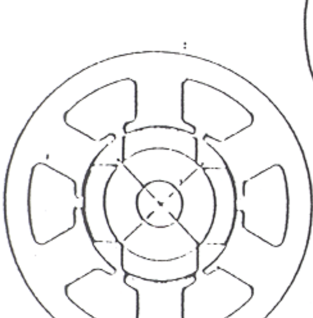


FIG 8-A

60° MAGNET

2.250 SLOTS PER POLE

18/8

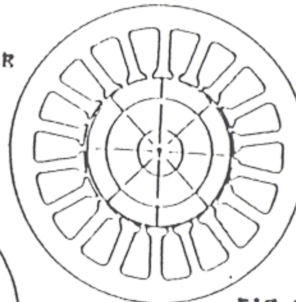


FIG 9-B

45° MAGNET

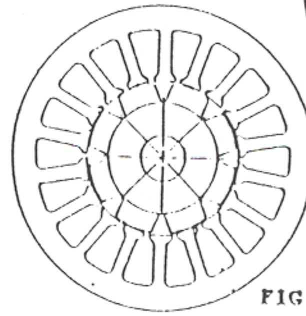


FIG 9-A

30° MAGNET

3.00 SLOTS PER POLE

12/4

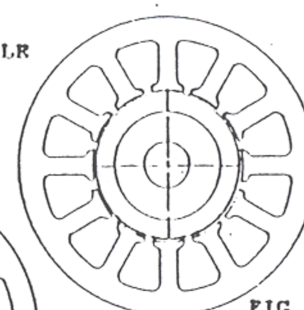


FIG 10-B

90° MAGNET

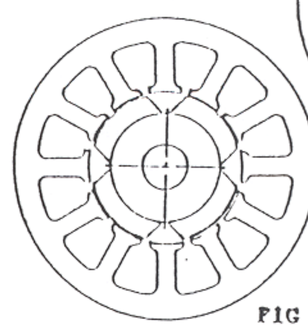


FIG 10-A

60° MAGNET

3.750 SLOTS PER POLE

15/4

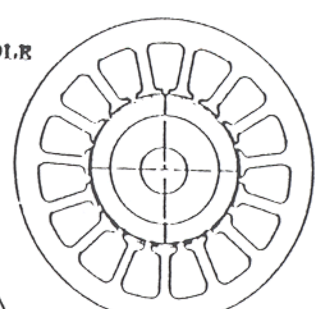


FIG 11-B

90° MAGNET

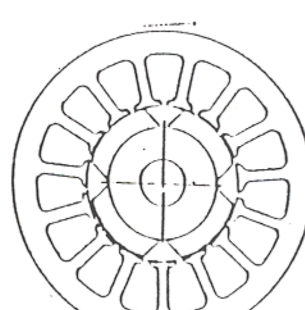
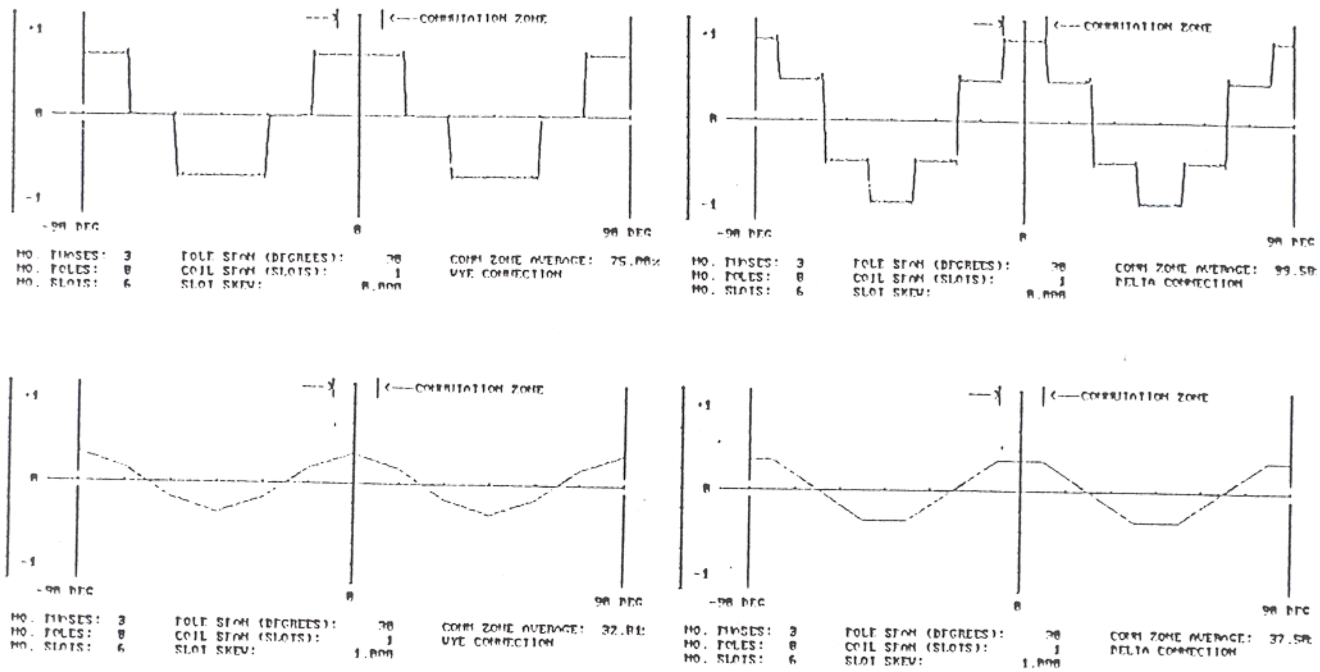


FIG 11-A

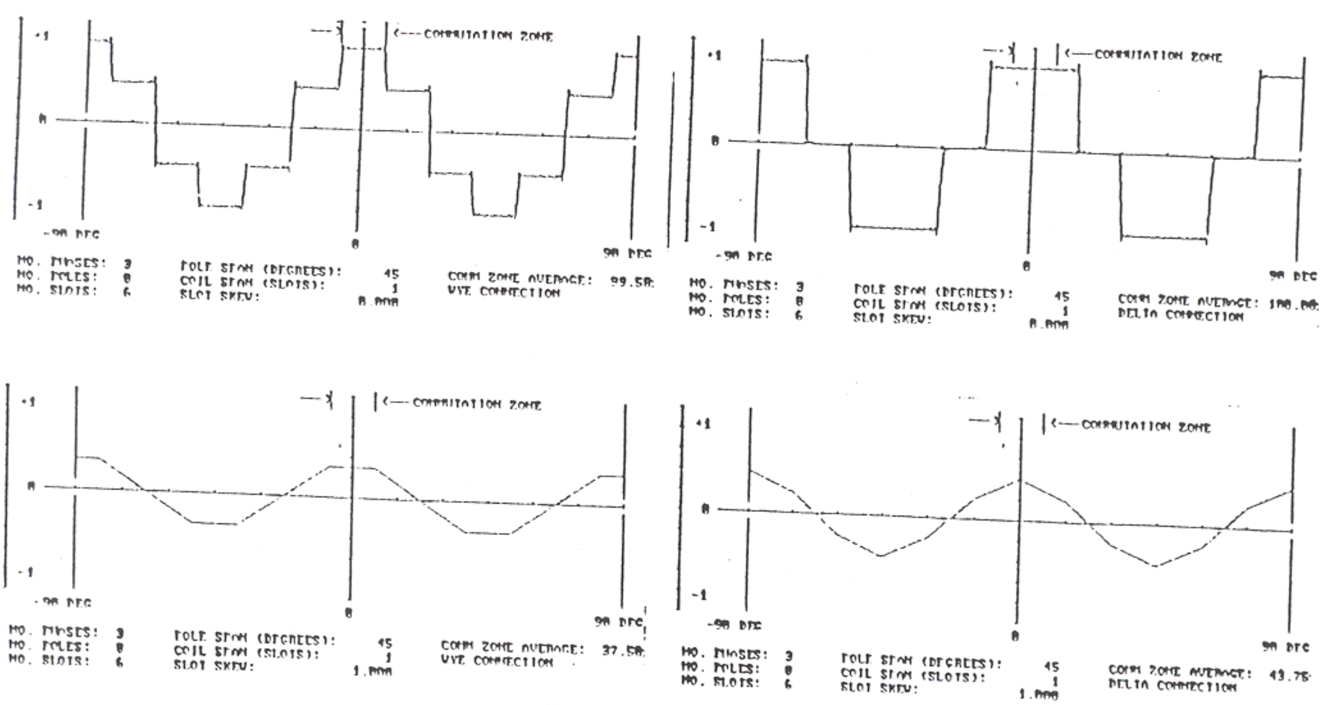
60° MAGNET

WYE CONNECTIONS

DELTA CONNECTIONS



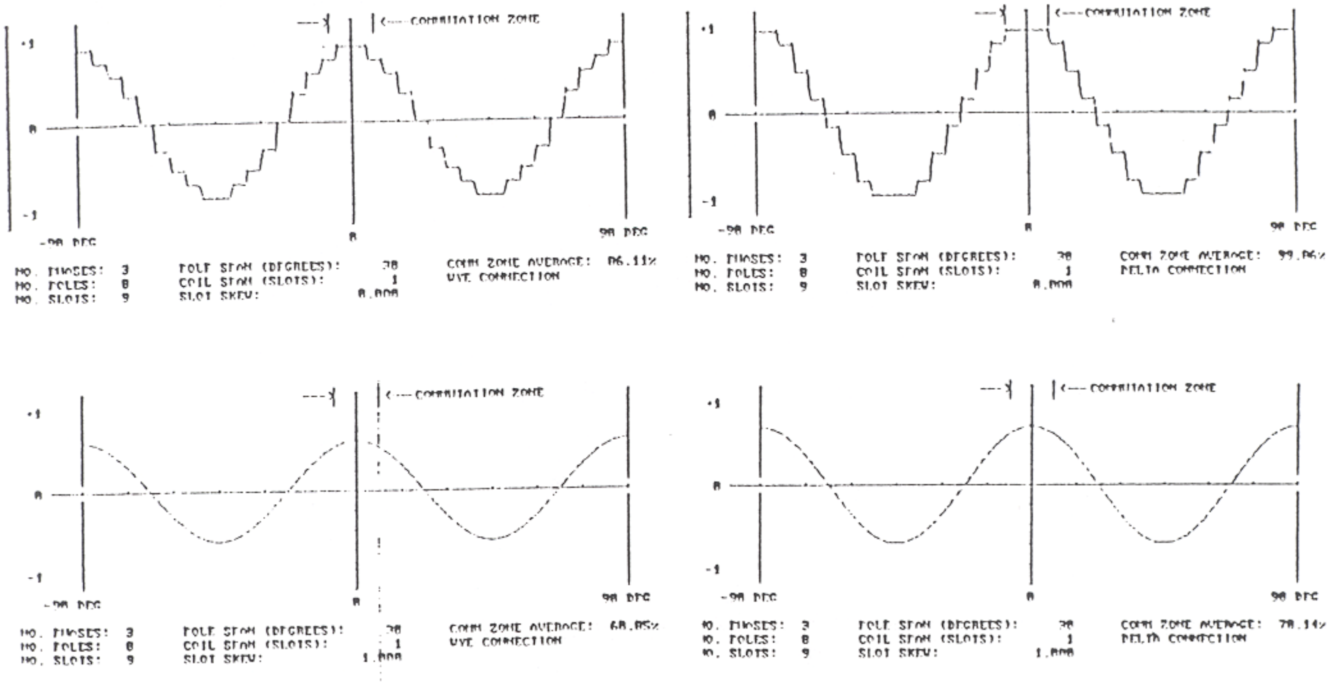

CURVES FOR FIGURE 6-A



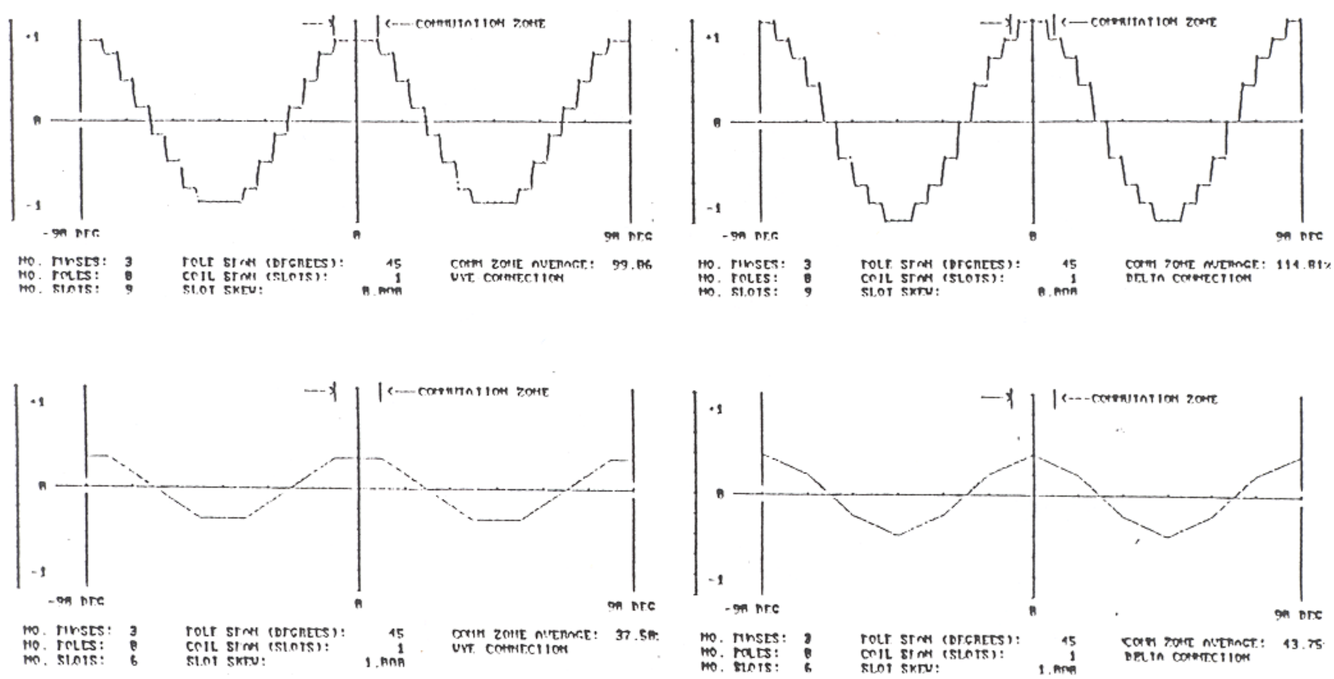

CURVES FOR FIGURE 6-B

WYE CONNECTIONS

DELTA CONNECTIONS



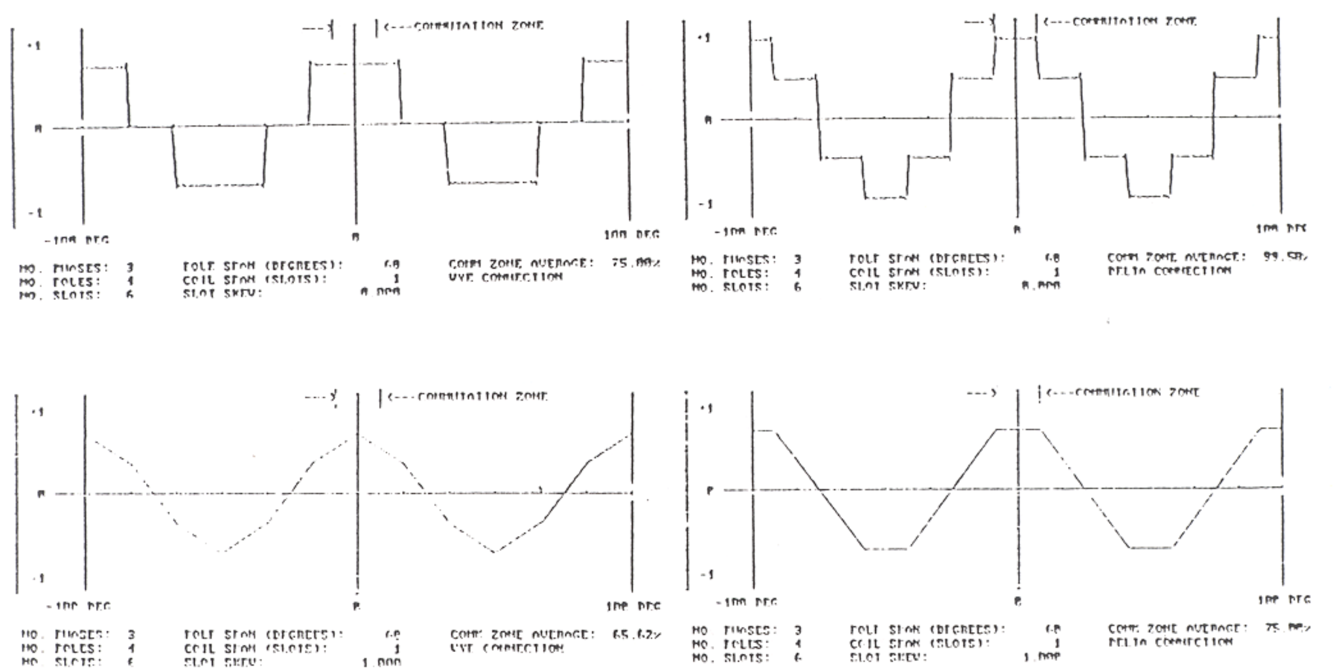

CURVES FOR FIGURE 7-A



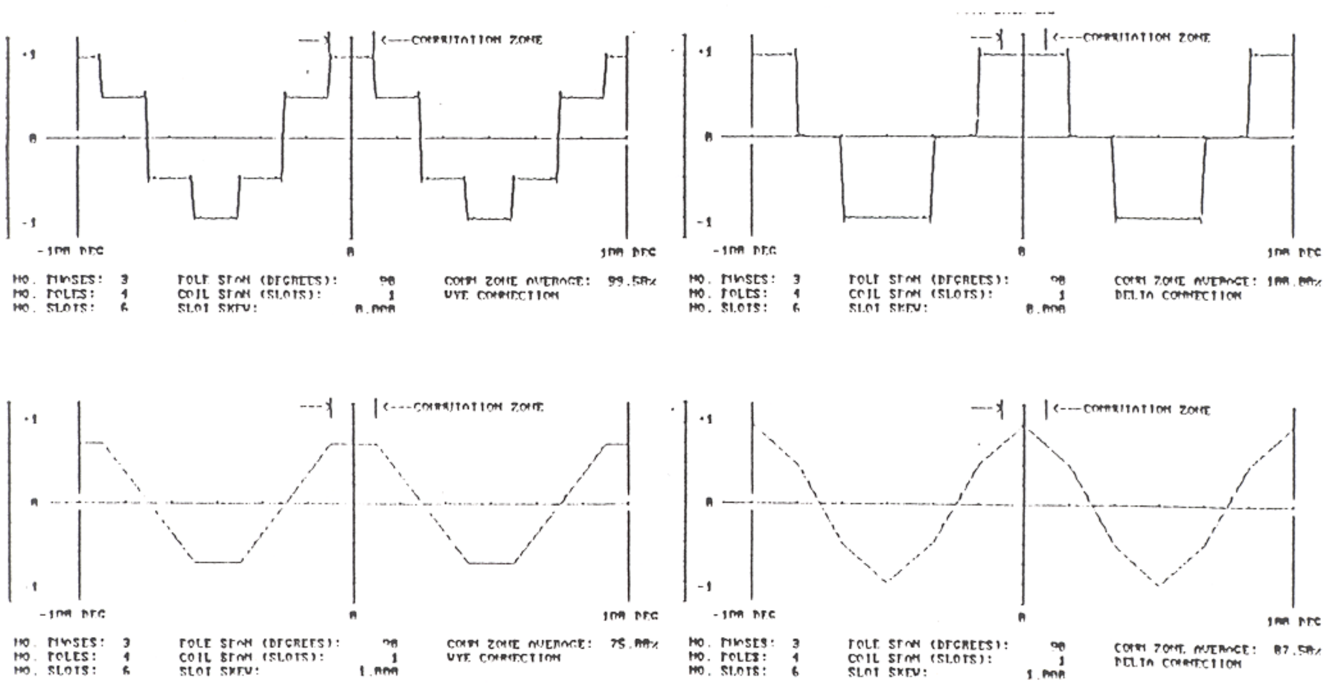

CURVES FOR FIGURE 7-B

WYE CONNECTIONS

DELTA CONNECTIONS



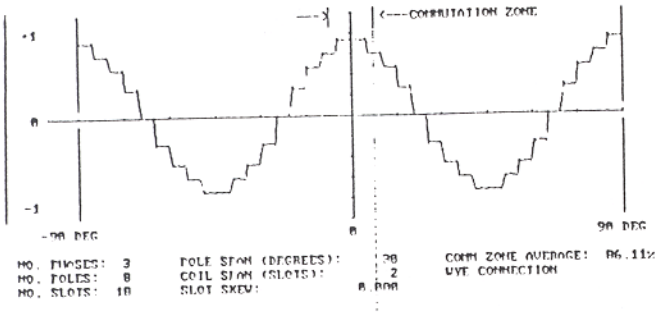

CURVES FOR FIGURE 8-A

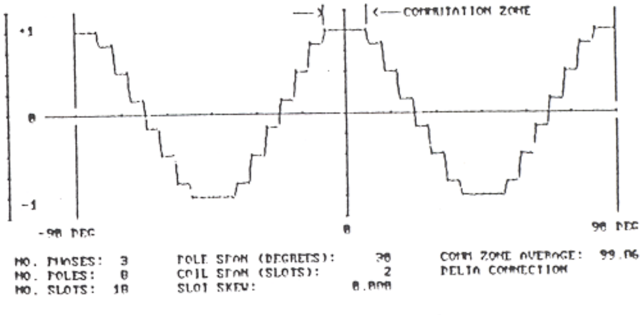


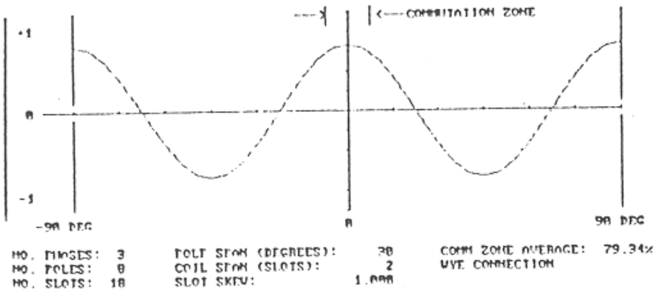

CURVES FOR FIGURE 8-B

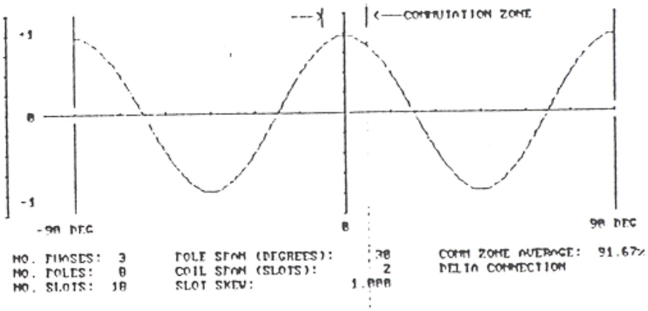
WYE CONNECTIONS

DELTA CONNECTIONS

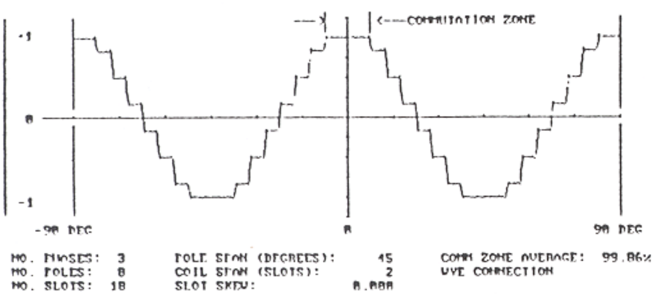


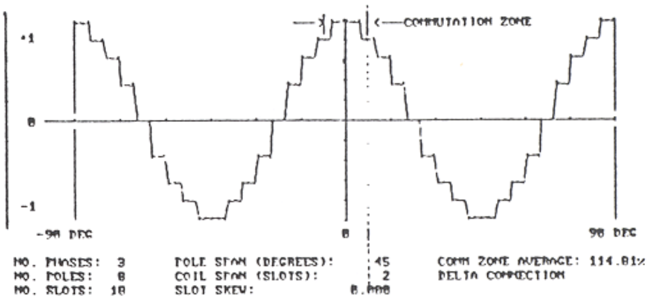



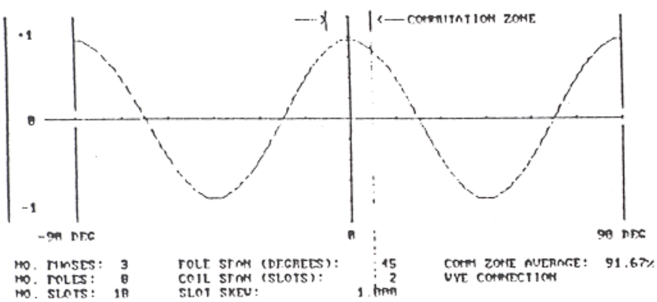



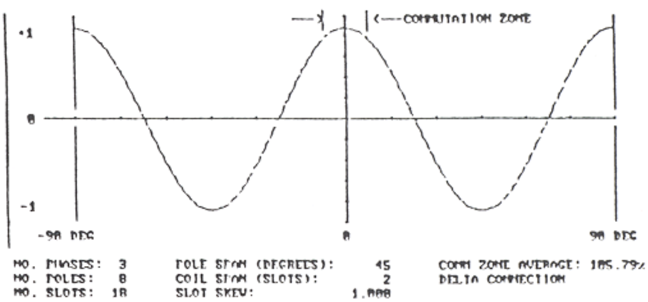




CURVES FOR FIGURE 9-A



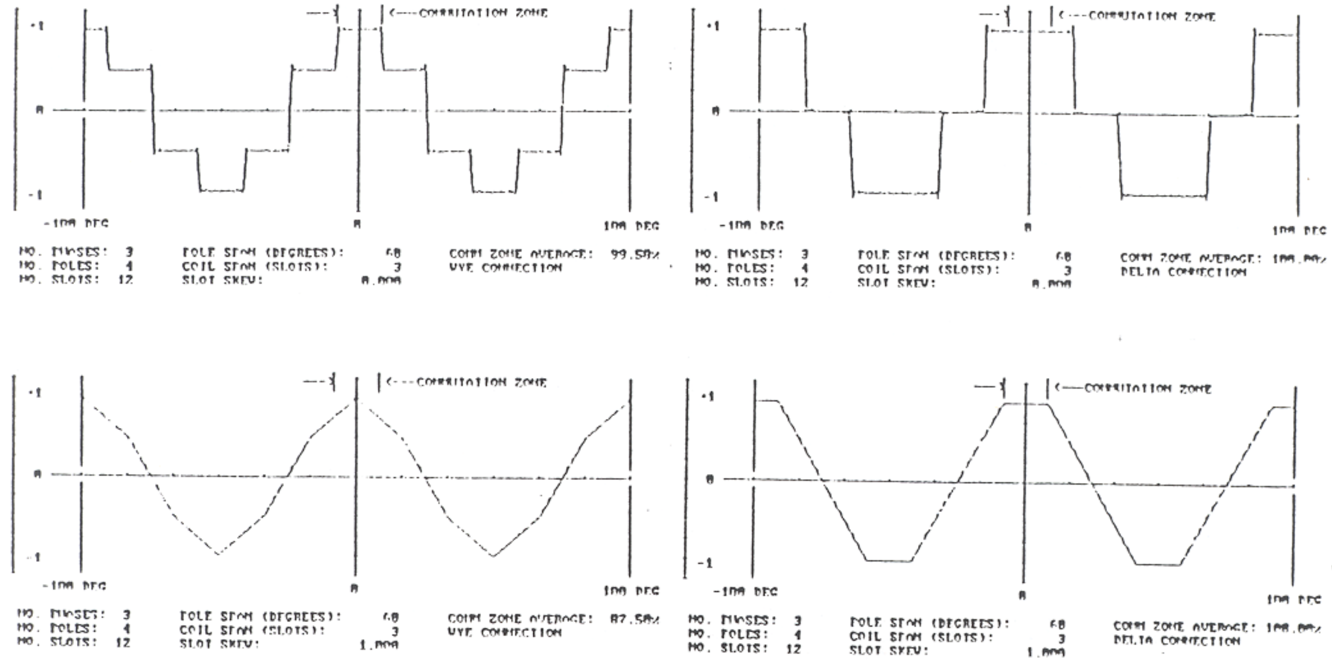



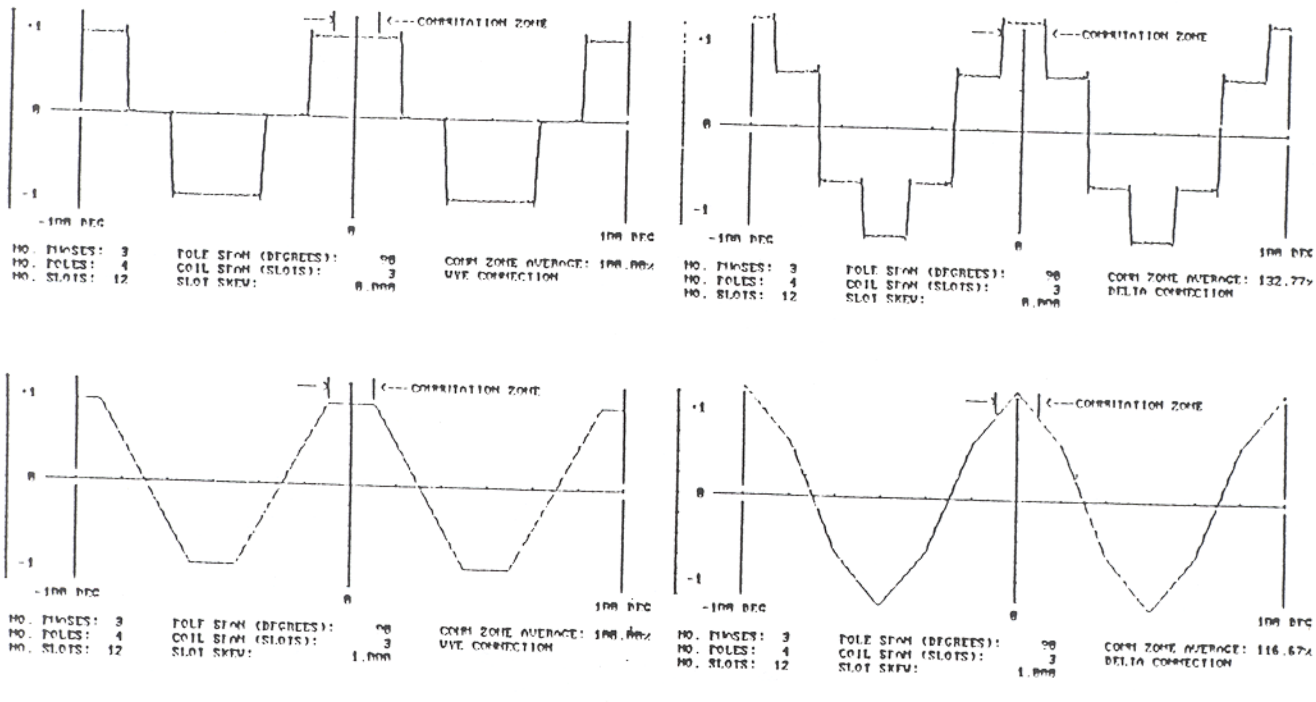

CURVES FOR FIGURE 9-B

WYE CONNECTIONS

DELTA CONNECTIONS

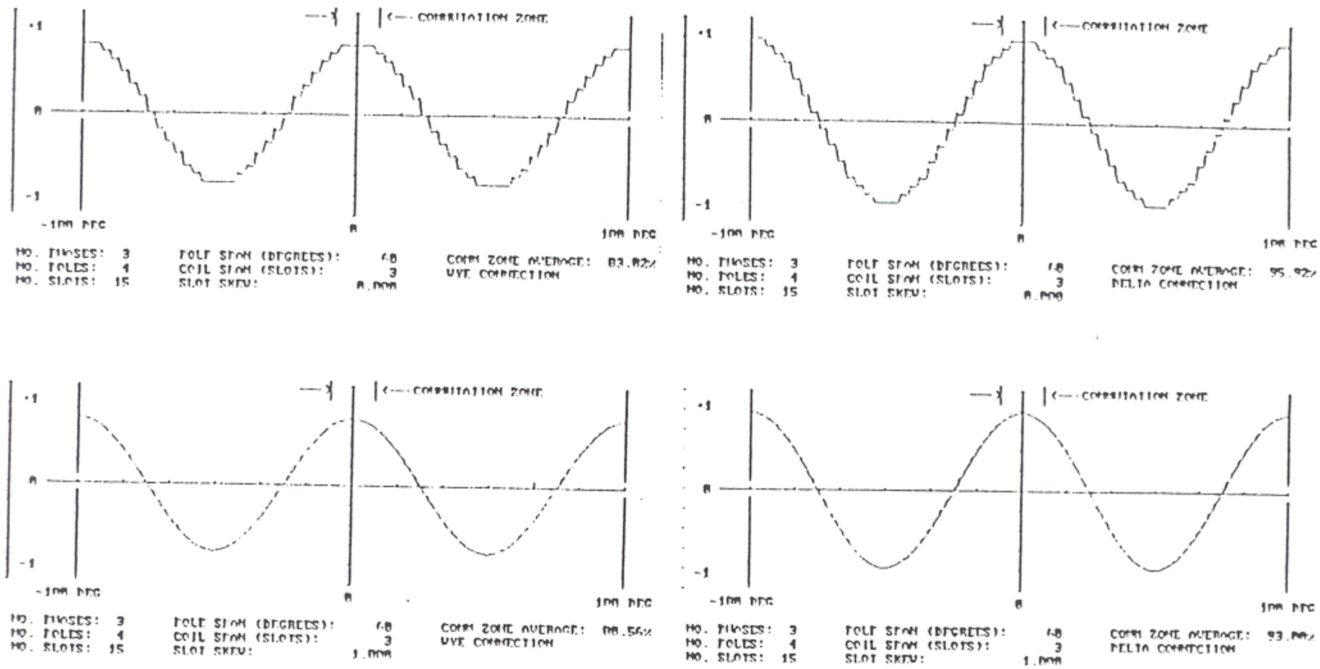



CURVES FOR FIGURE 10-A

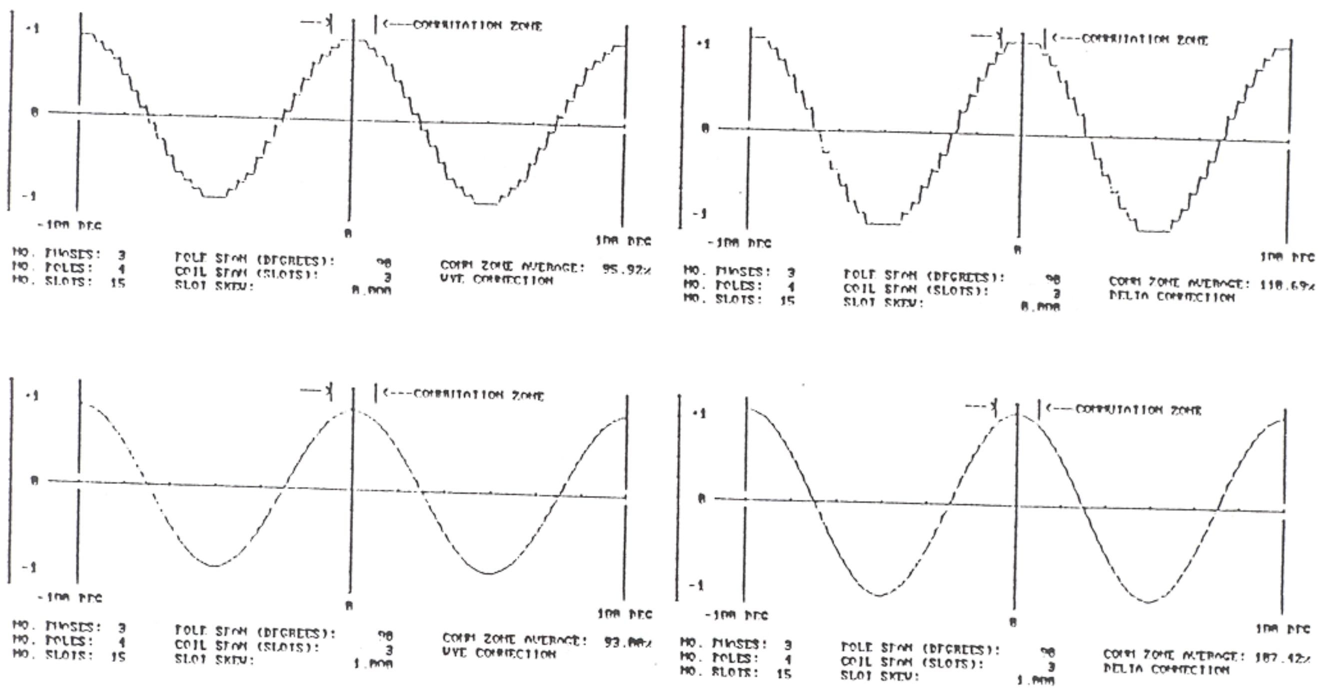



CURVES FOR FIGURE 10-B

WYE CONNECTIONS | DELTA CONNECTIONS




CURVES FOR FIGURE 11-A




CURVES FOR FIGURE 11-B

## VI CONCLUSION

Usually a three phase winding will be chosen because of power converter costs. The number of rotor poles should be considered based on magnet cost vs performance, inertia, speed and mechanical considerations. Once those two choices are made you can look up the data given here and select the best slot/winding configuration for your application.


## VII ACKNOWLEDGEMENT

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