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I am submitting herewith a thesis written by Oladokun E. Faduyile entitled “Effect of Harmonics on the Efficiency of a three phase Energy Efficient and Standard Motors.” I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment for the degree of Master of Science in Electrical Engineering concentrating in Power System.

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**EFFECT OF HARMONICS ON THE EFFICIENCY OF A
THREE PHASE ENERGY EFFICIENT AND STANDARD MOTORS**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Chattanooga

Oladokun E. Faduyile

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DEDICATION

This thesis is dedicated to God Almighty for seeing me through its completion....

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ABSTRACT

This study investigates the impact of harmonics on the performance, efficiency, and the economics of energy efficient motors (EEMs) and standard motors (STMs). In this research, the skin effect impedance model that incorporates the skin effect in the rotor bars is used to study the motor's behavior under harmonics.

The characteristic behavior of the motors are simulated using a computer program which compares the performance, efficiency, and the economics of these motors and identifies the harmonic level at which these behavior are most prominent. The following motor sizes 25, 50, 100, 150, 200, 250, and 300 hp are used in the execution of this study.

Verification of the skin effect impedance model is done by comparing the calculated current and efficiency at full load, with manufacturers supplied data under normal conditions. The efficiency of the standard motor and the energy efficient motor decreases as the order of harmonics increases. It is found that the 5th and 7th harmonics contributed over 45% and 25% respectively of the total rotor loss of both the EEM and STM. The rate of drop of the EEM efficiencies is greater than the rate of drop of efficiencies for the STM at the same load condition this implies that although the EEM is a much better design, it is more susceptible to harmonic due to the skin effect in the rotor bars. The payback analysis shows that the EEMs are more cost effective even when subjected to harmonic. However, the losses due to harmonics need to be minimized and further research need to be devoted to the losses at the 5th and 7th harmonics.

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CHAPTER 1

INTRODUCTION

The largest portion of electrical energy consumed is used by electric motors. Over half of all electrical energy consumption in the US is by electric motors and more than two third of electricity used by industry is electric motor (18). Improving the efficiency of electrical motors is of high priority.

In the last two decades, significant effort has been made by manufacturers of electric motors in the technique of construction of energy efficient motors (EEM). This effort has resulted in improvement in full-load efficiencies of electric motors. The Energy Policy Act (EPACT) of 1992 which was enforced in 1997 requires that all general purpose polyphase single speed squirrel-cage induction motors manufactured in the US rated from 1 – 200 horse power (hp) must meet minimum efficiency levels.

Motor efficiency standards have succeeded in transforming the motor marketplace, resulting in significant energy savings and carbon reductions. As a result of the standards that were enacted as part of the EPAct-92 (20).

The importance of this investigation is to further explore areas where energy efficient motors are still vulnerable to significant losses when subjected to non-sinusoidal source such as harmonics. It has been established that harmonics significantly impact the operation of standard motors but their effect on energy

efficient motors has not been fully investigated, also the harmonics order at which these losses are most significant has not be well documented.

1.1 Unresolved Problems

With the increase in number of harmonics generating devices more nonlinear loads are being applied to the power system. The application of these nonlinear loads has significantly contributed to voltage and current waveform distortion in power system (10). Nonlinear loads on induction motors result in an increase of current, higher power loss, heating of the rotor, a decrease of efficiency and consequently impact the operation of the motor.

The effects of harmonics on efficiencies and rotor losses on energy efficient motors have not been fully investigated. In addition, the harmonic orders that contributed to the most significant loss on the EEM have not been well evaluated and determined.

As a direct result of these nonlinear sources, a better understanding of the impacts of harmonics on EEM motors need to be further investigated.

1.2 Research Objective

The objective of this research is to study the losses due to harmonics on energy efficient motors and identify at what harmonic level these motor losses are most significant. This study also investigates the losses on standard motors under the same nonlinear load condition. Multiple motor sizes (25hp, 50hp, 100hp, 150hp, 250hp, and 300hp) were used for this study.

The efficiency of the EEM will be evaluated under this application by using the skin effect impedance model. This model accounts for the nonlinear dependence of rotor bar impedance with frequency (6)

Chapter 2 is a review of previously done research on motor efficiencies, harmonics effects, motor losses, skin effect impedance model, and the economics of motor efficiencies.

Chapter 3 covers the method used to conduct this research and the computer model used to implement this investigation.

Chapter 4 contains the results and discussions. The conclusions of this investigation are presented in chapter 5.

CHAPTER 2

LITERATURE REVIEW

Research that has been conducted on induction motors, nonlinear loads, harmonics orders, motor efficiencies and losses, and unbalance voltages is well documented. Numerous research studies have been done in finding ways to maximize the efficiency of energy efficient motors. However, there are still challenging areas that need further investigation such as the continuous effect of harmonics on energy efficient motors (EEM). Harmonics have been known in the electrical world since the first AC generator went online over 100 years ago (19) but their effects especially on energy efficient motors have not been fully investigated.

The review of previously done research helps in shaping the areas of investigation and the purpose of this study. It also provided opportunity for in depth understanding of effect of harmonic on EEM.

2.1 Energy Efficient Motors

In order to understand the concept of energy efficient motors, efficiency will be discussed. Efficiency of a motor can be described as a measurement of the motor's ability to convert electrical energy into mechanical energy. This is measured by the motor's useful power output divided by the total power input. It's usually expressed as a percentage.

There are two major methods used to calculate the efficiency of the motor, the direct method and the indirect method.

In the direct method, both the input and output are used in the calculation of efficiency as

$$Efficiency = \left(\frac{Output}{Input} \right) * 100 \quad (2.0)$$

In the indirect method, take into account losses associated with the motors and express efficiency in either of the forms shown in equations 2.1 or 2.2

$$Efficiency = \left(\frac{Input - Loss}{Input} \right) * 100 \quad (2.1)$$

or

$$Efficiency = \left(\frac{Output}{Output + Loss} \right) * 100 \quad (2.2)$$

The National Electrical Manufacturers Association (NEMA) started the practice of marking on motor nameplates efficiency derived from a specific test in 1980 (EASA).

All non exempt general purpose motors manufactured for use in the United States must meet the nominal efficiencies as stated by NEMA. However, motors built overseas, by manufacturers not member of NEMA fall outside these requirements and are not bound that a particular ‘minimum’ efficiency exists for their design.

The term “energy efficient” motors or lately “premium” motors are motors that that are more efficient in converting electrical energy into mechanical energy than comparable standard motors (18).

These motors have been developed with more generous electrical and magnetic circuit and superior components that have enhanced the overall efficiency of the motor. Since these motors are well developed and designed, the motors require less power and current to operate and have higher power factor compared to the standard motors. However, they are more prone to unbalanced behavior due to the skin bar effect in the rotor.

2.2 Losses in Induction Motors

Losses in induction motors can be categorized into five major types. The primary I^2R loss which is the ohmic loss that is due to the stator windings. The secondary ohmic, I^2R loss which is due to the rotor bars and end rings of the motor is the second type of induction motor losses. The third type of loss is the loss in the iron core of the motor. Friction and windage loss in the induction motor is considered the fourth, while the fifth and most elusive is the load stray loss.

Minimizing these losses has been attempted by methods such as increasing the copper winding wire size around the stator core, addition of material to the rotor bars, using electromagnetic silicon steel instead of the standard carbon steel, using smaller and more efficient fans for the cooling inside the motor, and by systematically reducing the air gap between the stator and rotor.

The effect of harmonics on induction motors which affects the stator, the motor core and the rotor is a major contributing factor to motor losses. While work has been done on harmonics and its effect on induction motors, a thorough and extensive work has not been done on its effects on energy efficient motors.

2.3 Harmonics

An ideal induction motors built with field distributed stator and field windings and operating in a uniform magnetic field will produce a true sinusoidal voltage. However, since an ideal situation cannot be realized in a real life situation, distortion of the voltage waveform is created and causes the voltage time relationship to deviate from the pure sine function. This distortion is the form of periodic functions known as harmonics.

A harmonics is the component frequency of the wave signal that is an integral multiple of the fundamental (60Hz is USA) frequency; 120Hz, 180Hz, 240Hz, etc. Harmonics are designated by their harmonic number or multiples of the fundamental frequency. For example, the 3rd harmonic is three times the fundamental frequency (180Hz) and the 5th harmonic is five times the fundamental frequency (300Hz).

Harmonics are readily generated in an induction motor with the inverse use of variable frequency drives (VFD). These harmonics are generated by inverters by the order below:

$$n = kp \pm 1 \quad (2.3)$$

where

n = order of harmonics

k = integer 1, 2, 3, ...

p = number of pulses of the inverters

For example, a six pulse/pole inverter will generate the following characteristics harmonics, 5th, 7th, 11th, 13th and so forth.

In an ideal and normal operational condition, the slip, s of an induction motor is insignificant in such that the slip associated with each harmonic for any harmonic frequency is given by:

$$S_n = \frac{kp + s}{kp \pm 1} \quad (2.4)$$

where,

$S_n = \text{harmonic slip}$

$s = \text{rated slip of the motor}$

$k = \text{integer } 1, 2, 3, \dots$

$p = \text{number of poles of the inverter}$

2.4 **Skin Effect**

Skin effect is the phenomenon where an alternating electric current distributes itself at the surface (skin) of the conductor resulting in a greater current density at the surface of the conductor as compares to the core.

The dynamic impedance of the rotor bars of the induction motor is influenced by the frequency of the current flowing through the rotor bars. The skin effect influence depends greatly on the rotor bar design. It is minimal in case of wound rotor or single cage motors and greatly pronounced in case of double cage and deep bar motors (2).

2.5 Economics

The cost effectiveness of an energy-efficient motor in a specific situation depends on several factors, including motor price, efficiency rating, annual hours of use, energy rates, cost of installation, and downtime.

There are multiple established methods in evaluating the economic gains of energy efficient motors over standard motors. The simplest one is the simple payback method usually used for individual or small quantities of motors. The annual cost savings of the energy efficient motor over the equivalent standard motor can be calculated using

$$S = 0.746 * hp * L * C * N * \left[\frac{100}{E_B} - \frac{100}{E_A} \right] \quad (2.5)$$

where,

S = annual savings in \$/year

L= percentage of full operating load

C = cost of electricity in \$/KWH

N = running time in hr/yr

E_B = standard motor efficiency under actual load condition

E_A = energy efficient motor efficiency under actual load condition.

The second method is the use of efficiency evaluation factor usually used for large groups of motors that run the same number of hours per year at the same power costs (17). The efficiency factor can be expressed in dollar per kilowatt as shown below

$$EF(\$/kw) = C * N * n \quad (2.6)$$

where,

C = average energy cost, \$/kw

N = running time, hr/yr

n = period of evaluation of number of years of operation

The evaluation factor can then be used to find the life cycle savings (LCS) using

$$S = 0.746 * hp * EF \left[\left(\frac{100}{E_B} - \frac{100}{E_A} \right) \right] \quad (2.7)$$

Other methods as described by (6) are the comprehensive evaluation method that takes into account the time value of money and the impact of inflation on power costs to determine the Present Worth Evaluation Factor (PWEF) and the Concise Saving Evaluation Method that compares the motors to be evaluated to a perfect motor which would have an efficiency of 100 percent. The present worth cost of losses over the motor life cycle is then evaluated.

CHAPTER 3

METHODS OF INVESTIGATION

A computer program based on the skin effect impedance model developed by Orthmeyer (2) was written to simulate the comparison of different energy efficient motors and standard motors (25, 50, 100, 150, 200 and 300 hp) sizes. The efficiencies of these motors were computed and compared as well as the economic impacts of these motors.

The motor data sheets were supplied by the manufacturer and applicable information about the data are presented in Appendix B. An economic evaluation method was developed to analyze the cost of operating the motors based on innovation discussed in an earlier chapter.

3.1 Skin Effect Impedance Model

This skin effect impedance model is an electrical machine theory which is a simplification of the skin effect electrical transient model. This model is capable of calculating the rotor bar current distribution, but neglects the electrical transients (2).

It represents the nonlinear relationship between rotor bar impedance and frequency. The fundamental frequency and successive harmonics circuits of the skin effect impedance model under steady state condition are shown in figure 3.1.

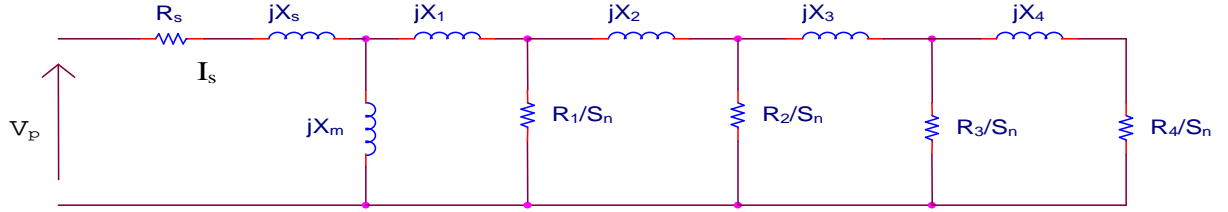


Figure 3.1: The skin effect impedance model

The different parameters of the model are calculated using the manufacturers supplied data for r_s , X_s , X_m , r_r , r_{rstart} and S_n . The value of rotor harmonic resistance is approximated from the following linear approximation equation,

$$r_f = (r_{rstart} - r_r) * (n - S) + r_r \quad (3.1)$$

where n is the harmonic number and r_f is the rotor negative sequence resistance of the motor.

The value of internal inductance L_{ii} , is

$$L_{ii} = r_f^2 / r_r \quad (3.2)$$

The rotor bar equivalent circuit parameters L_1 , L_2 , L_3 and L_4 are

$$L_1 = L_{ii} * 0.1 \quad (3.3)$$

$$L_2 = L_{ii} * 0.2 \quad (3.4)$$

$$L_3 = L_{ii} * 0.3 \quad (3.5)$$

$$L_4 = L_{ii} * 0.4 \quad (3.6)$$

The external inductance X_{gap} , is found from the equation (3.7)

$$X_{gap} = X_r - L_{ii}/3$$

The parameters X_1 , X_2 , X_3 , X_4 of the skin effect impedance model are calculated by summing up the inductances (16).

$$X_1 = X_{\text{gap}} + L_1/2 \quad (3.8)$$

$$X_2 = L_1/2 + L_2/2 \quad (3.9)$$

$$X_3 = L_2/2 + L_3/2 \quad (3.10)$$

$$X_4 = L_3/2 + L_4/2 \quad (3.11)$$

The constant resistance values of the models are calculated by the following equations

$$R_1 = r_r/0.1 \quad (3.12)$$

$$R_2 = r_r/0.2 \quad (3.13)$$

$$R_3 = r_r/0.3 \quad (3.14)$$

$$R_4 = r_r/0.4. \quad (3.15)$$

These constant resistances are converted to variable resistances that vary with frequency when they are divided by respective slip, S at that harmonic order.

3.2 Fourier Transform

The Fourier transform is a versatile tool used in many fields of science as a mathematical tool to alter a problem to one that can be more easily solved. The Fourier transform decomposes a signal or a function into a sum of sines and cosines of different frequencies which sum up to the original signal or function. The main advantage of the Fourier transform lies in its ability to transfer the signal from the time domain to the frequency domain which usually contains more information about the analyzed signal (11).

The Discrete Fourier Transform (DFT) is a form of Fourier transform that expresses an input function which is discrete and finite in terms of a sum of sinusoidal components by determining the amplitude and phase of each component.

These properties makes the DFT ideal for processing information stored in computers. In particular, the DFT is widely employed in signal processing and related fields to analyze the frequencies contained in a sampled signal and solve other mathematical operations.

As power system disturbances are subject to transient and non-periodic components, the DFT alone may fail to provide an accurate signal analysis. A much faster algorithm called the Fast Fourier Transform (FFT) was developed by Cooley in 1965.

This algorithm makes the computation speed for analyzing a Fourier signal much faster. The computation time for the FFT is proportional to $N \log_2(N)$, where N is the number of points in the series (11).

The sequence of N complex numbers x_0, \dots, x_{N-1} is transformed into the sequence of N complex numbers X_0, \dots, X_{N-1} by the DFT according to the formula:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N} kn} \quad k = 0, \dots, N - 1 \quad (3.16)$$

where e is the base of the natural logarithm and i is the imaginary unit ($i^2 = -1$).

3.3 Harmonic Model

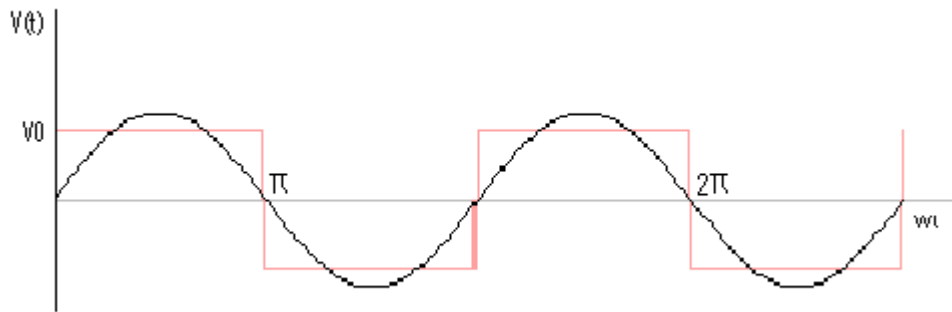


Figure 3.2: Sinusoidal Wave

Any single-valued, finite and continuous function $V(t)$ having a period of $2\pi/\omega$, may be expressed as the Fourier series

$$V(t) = \frac{v_o}{2} + \sum_{n=1}^{\infty} \left[v_n \cos(n\omega t) + v'_n \sin(n\omega t) \right] \quad (3.17)$$

- where v_o is the fundamental voltage (peak to peak)

This equation represents a function in terms of the fundamental frequency and its harmonics. Each frequency is an integer multiple of the fundamental system frequency as shown in Figure 3.3.

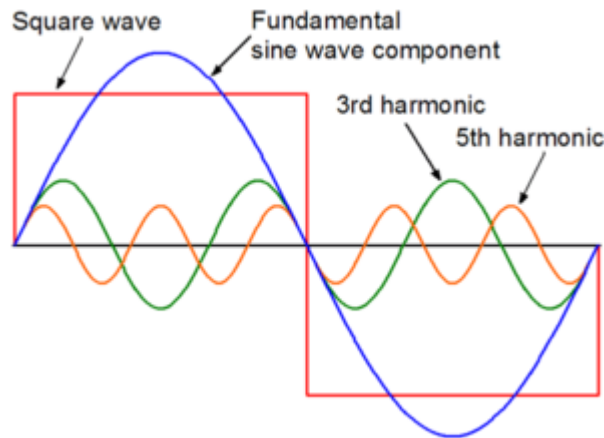


Figure 3.3: Harmonic Waveform

The harmonic content of waveform used in this study and the corresponding voltage in percent of the fundamental voltage is shown in Table 3.1 (3).

Table 3.1: Voltage in % of Fundamental

Harmonic Level	Voltage in % of Fundamental
3	33.3
5	20.0
7	14.3
9	11.1
11	9.1
13	7.7
15	6.7
17	5.9
19	5.3
21	4.8
23	4.3
25	4.0

Harmonic Level	Voltage in % of Fundamental
27	3.7
29	3.4
31	3.2
33	3.0
35	2.9
37	2.7
39	2.6
41	2.4
43	2.3
45	2.2
47	2.1
49	2.0

When these harmonic voltages are applied to the induction motor, the resultant harmonic phase currents produce a stator magnetomotive force (MMF) that travels at n times the velocity of the synchronous speed, ω_s of the fundamental stator MMF.

The harmonics from converter equipment on a polyphase system is given as (8)

$$n = 3k \pm 1 \quad (3.18)$$

where n is the harmonic number and k is any integer.

The phase sequence of the harmonic voltages of this relation resulted in opposite and same sequence of the fundamental. The opposite sequences of the fundamental are denoted as negative for $n = 3k-1$ and the sequence in phase with the fundamental are denoted as positive sequences for $n = 3k+1$.

$$(3.19)$$

$$(3.20)$$

The per unit slip of an induction motor is given as

$$S = \frac{\omega_s - \omega_r}{\omega_s}$$

$$\omega_r = (1 - S)\omega_s$$

where ω_s is the stator speed and ω_r is the rotor speed.

For any harmonic frequency the slip can be calculated as shown below, the corresponding harmonic frequency is shown in table 3.2.

$$S_n = \frac{n\omega_s - (1 - S)\omega_s}{n\omega_s} \quad (3.21)$$

$$S_n = \frac{(3k \mu 1)\omega_s - (1 - S)\omega_s}{(3k \mu 1)\omega_s} \quad (3.22)$$

$$S_n \cong \frac{3k \pm S}{3k \mu 1} \quad (3.23)$$

Table 3.2: Rotation and Slip Versus Harmonic

k	n	Rotation	S_n
1	2	-	(3-S)/2
1	4	+	(3+S)/4
2	5	-	(6-S)/5
2	7	+	(6+S)/7
3	8	-	(9-S)/8
3	10	+	(9+S)/10
4	11	-	(12-S)/11
4	13	+	(12+S)/13
5	14	-	(15-S)/14
5	16	+	(15+S)/16
6	17	-	(18-S)/17
6	19	+	(18+S)/19
7	20	-	(21-S)/20
7	22	+	(21+S)/22
8	23	-	(24-S)/23
8	25	+	(24+S)/23

3.4 Motor Losses

The losses associated with these motors can be categorized into five major types. The first type of loss is the primary I^2R loss which is the copper loss that is due to the stator windings. The secondary I^2R loss is considered the second type of induction motor loss. This loss is due to the rotor bars and end rings of the motor.

The third type of induction motor loss is the losses in the iron core of the motor. Friction and windage loss in the induction motor which is caused by the friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts are considered the fourth type of motor loss. The fifth and most elusive is the stray load loss. The stray load losses arise from variety of sources and are very difficult to identify or measure.

At each of the harmonic levels these losses are calculated and are used to calculate the efficiency of the motor. However, since the no load loss provided by the motor vendor can represent the friction, windage and iron core losses of the motor, they are considered constant regardless of the harmonic level.

The skin effect impedance model equivalent circuits of a three-phase induction motor are shown in Figure 3.4.

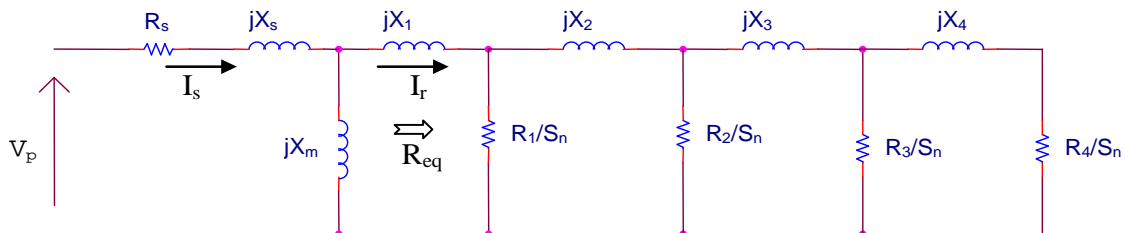


Figure 3.4: The skin effect impedance model

Where R_s and X_s refer to the stator resistance and reactance respectively, X_m is the magnetizing reactance, I_s and I_r are the stator and the rotor current. S_n is the slip of the motor which is dependent on the harmonic order as shown in Table 3.2. R_{eq} is the equivalent motor impedances looking into the rotor as shown in Figure 3.4.

Calculating Motor Losses:

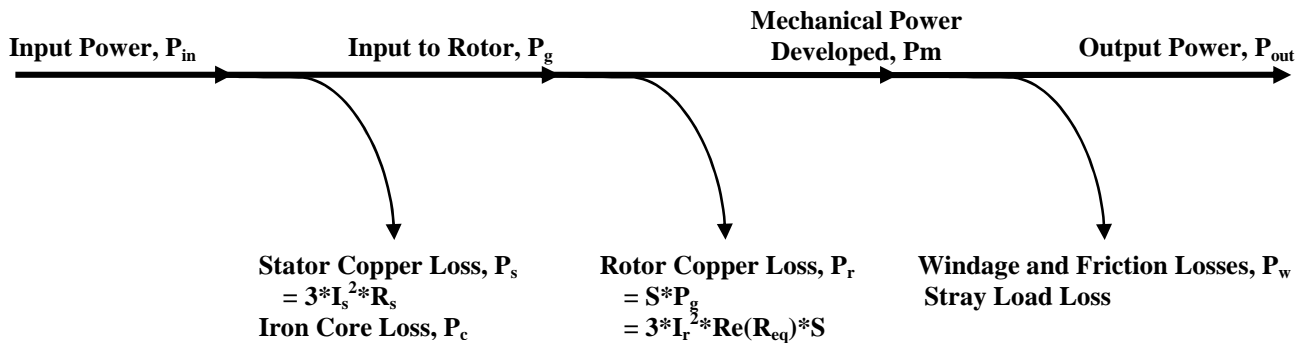


Figure 3.5: Power Flow in an Induction Motor

Input Power

The total electrical power input can be calculated as shown in 3.24.

$$P_{in} = \sqrt{3} * V_p * I_s * \cos(\theta) \quad (3.24)$$

where, V_p , I_s , and $\cos(\theta)$ are the fundamental voltage, stator current and the power factor of the motor respectively.

Stator Loss

The formula to calculate the stator loss of the motor is given by

$$P_s = 3 * I_s^2 * R_s \quad (3.25)$$

where, R_s is the stator resistance.

Rotor Loss

The power transferred across the air gap, P_g which is also known as the rotor input power is first calculated as shown below. The rotor resistance loss is then calculated based on the slip of that harmonic order as shown

$$P_g = 3 * I_s^2 * R_g \quad (3.26)$$

where R_g is the real part of the parallel combination of jX_m and R_{eq}

$$P_r = S * P_g \quad (3.27)$$

The rotor loss can also be calculated using equation 3.28

$$P_r = 3 * I_r^2 * \text{Re}(R_{eq}) * S \quad (3.28)$$

Stray Losses

Stray loss cannot be easily calculated. It is actually the sum of several smaller losses that are dependent on the motor operation. For this study, the stray loss is assumed to be 0.5% of the total input power at each harmonic order based on International Electrotechnical Commission, IEC standard. So,

$$P_{\text{strayLoss}} = 0.005 * P_{\text{in}} \quad (3.29)$$

Total Losses

The total motor loss is calculated by adding the calculated losses of the stator copper loss, rotor copper loss, and the calculated stray load loss to the no load loss supplied by the motor vendor. The no load loss comprises the iron core loss, stray load loss, windage and friction losses. However, to calculate the total loss at the fundamental, equation 3.30 is used.

$$P_{\text{TotalLoss}} = P_{\text{fullLoadLoss}} \quad (3.30)$$

The total loss at subsequent order of harmonics is given as

$$P_{\text{TotalLoss}} = P_s + P_r + P_{\text{noLoad}} + P_{\text{strayLoss}} \quad (3.31)$$

Total Output Power

The total output power is calculated by subtracting total losses from the total input power and is given by

$$P_{\text{out}} = P_{\text{in}} - P_{\text{fullLoadLoss}} \quad (3.32)$$

The total output power at subsequent order of harmonics is given as shown below

$$P_{\text{out}} = P_{\text{in}} - (P_r + P_s + P_{\text{noLoad}} + P_{\text{strayLoss}}) \quad (3.33)$$

Motor Efficiency

The efficiency of the motor is calculated by considering the losses rather than direct calculation of input and output ratio. The efficiency of the motor is given by

$$\text{Efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{P_{\text{in}} - P_{\text{TotalLoss}}}{P_{\text{in}}} * 100 \quad (3.34)$$

3.5 Economic Evaluation

The overall goal of the study is to show how harmonics can further put a burden on the efficiency and the cost of operating energy efficient motors. It has been established that energy efficient motors produce higher savings over the life cycle of the motor based on the economic evaluation comparison of energy efficient motors and standard motors. However, not enough adequate work has been done to further maximize the savings of the operations of energy efficient motor.

In calculating the economic saving of these efficient motors the modified simple pay back approach will be used. The established method will be modified to show that that

additional savings could be achieved if the effect of harmonics is minimized on these motors. The modified simple payback analysis equation as shown in equation 2.5

$$S = 0.746 * hp * EF \left[\left(\frac{100}{E_B} - \frac{100}{E_A} \right) \right] \quad (3.35)$$

where

S = annual savings in \$/year

L = percentage of full operating load

C = cost of electricity in \$0.12/KWH

N = running time in 8640/yr

E_h = motor efficiency of EEM under harmonic load condition

E_f = motor efficiency of STM under harmonic load condition.

CHAPTER 4

RESULTS AND DISCUSSION

A thorough investigation of the impact of harmonics on the operation of energy efficient motors and the standard motors was conducted with the aid of computer programs using Matlab software and using the data supplied by the motor manufacturer. The computer program compares the characteristic behavior of these motors (EEMs and STMs) at the fundamental frequency and at different orders of harmonics. The manufacturer supplied data used is given in Appendix B. All values displayed on the graph are in per unit, (p.u), and percentages.

4.1. Losses Due to Harmonics

Each of the EEM and STM were analyzed utilizing the computer program developed. The result of the analysis as shown in the graph section shows that the STM has more total loss than the EEM. This conclusion is expected since the EEM is better designed to compensate for this loss; hence the focus is on the secondary ohmics loss, the rotor loss. The rotor loss is dependent on the speed and the frequency at which the motor is operating and due to this understanding and the discussion of the electrical impedance model, the rotor loss of the EEM is much greater than that of the STM.

Each STM and EEM followed trend of higher rotor losses. For the 25hp motors, the rate of increase of rotor loss for the STM motor is 7% while that of the EEM motor is 10.7%. For the 50hp motors, the rate for STM and EEM are 10.6% and 10.4% respectively. The rate of increase in rotor loss for the 100hp STM is 9.38% and that of the EEM is

11.43%. However as the rating of the motor increases, it was observed that the rate of increase in the rotor for the STM became slightly higher or about the same. For the 150hp the rate of increase in rotor loss for the STM is 6.64% as against 3.97% for the EEM. Likewise for the 200hp, the rate of increase in rotor loss for the STM is 7.17% as against 3.96% for the EEM. The rate of increase for 250hp for the STM and EEM are practically the same at 5.51% and 5.54% respectively. Likewise the rate of increase of the 300hp for the STM and EEM are 5.31% and 5.28%. These differences for the higher rating EEMs might be due to possible differences in rotor bar and end rings design as well as the motor's composition.

In all, the largest percentage increase in rotor loss for the EEM is 11.43% at 100hp and for the STM is 10.41% at 50hp. The smallest percentage increase in rotor loss for the EEM is 3.96% at 200hp and that of the STM is 5.31% at 300hp.

The largest cumulative rotor loss in per unit for the STM and EEM are 0.8703 and 0.8952 at 200hp and 250hp respectively while the smallest summation of rotor loss per unit for the STM and EEM are 0.8451 and 0.8053 at 100hp and 150hp respectively.

4.2. Motor Efficiencies

The efficiencies of each Standard Motor and energy efficient motor were analyzed at each order of harmonics. The overall trend shows that the efficiencies of STM and corresponding EEM decrease as the order of harmonics increases.

The rate of drop of efficiencies for each STM and EEM are as shown in the graph section. The percentage drop in efficiency for the 25hp EEM and STM are 1.07% and 0.88% respectively. For the 50hp the percentage decrease in efficiencies are 1.02% and

1.23% for the EEM and STM respectively and for the 100hp, the percentage decrease in efficiencies are 1.01% for EEM and 0.93% for the STM. The drop in efficiencies for 150hp are 0.17% for EEM and 0.55% for STM, likewise the percentage decrease in efficiencies for the 200hp are 0.15% for EEM and 0.54% for STM. The percentage decrease in efficiencies for 250hp EEM and STM are 0.27% and 0.38% while the drop in efficiencies for the 300hp EEM and STM are 0.23% and 0.34% respectively.

The percentage decrease of efficiencies for the smaller rating EEM and STM (100hp and below) are much higher than that of the higher rating motors (above 100hp). The largest percentage decrease in efficiencies is 1.07% for the EEM at 25hp and 1.23% for the STM at 50hp. The smallest percentage decrease in efficiencies occurs for the 200hp EEM at 0.15% and 0.34% for the 300hp STM.

4.3. Economics

The data from the computer analysis clearly supports that energy efficient motors is more cost effective than the Standard Motors. The rate of break even or payback for initial cost of procuring efficient motors as compared to the inefficiencies of the Standard Motors is very minimal.

The average savings per year and payback period for the 25hp motors are \$328 and 1.29years. For the 50hp motors, the payback period is 4.6years and annual savings is \$480. The savings per year for the 100hp motors is \$1260 while its payback period is 1.34years. The yearly savings for the 150hp motors is \$1800 and its payback period is 1.35years. The savings per year for the 200hp motors is \$1700 while its payback period is 1.75years. For

the 250hp motors, the payback period is 1.3years and annual savings is \$2520. The yearly savings for the 300hp motors is \$2430 and its payback period is 1.26years.

The highest annual savings achieved from the simple payback analysis is \$2520 for the 250hp motors while the shortest payback period is 1.26years for the 300hp motors. The longest payback period is 4.6years for the 25hp motors.

Graphical reports

The graphs shown in Figures 4.1 – 4.70, obtained from the computer analysis for this study were grouped according to their motor rating. There are total of 10 graphs for each of the 25, 50, 100, 150, 200, 250, and 300hp motors. Each of the graphs show the overall analysis of this study based on their corresponding rating.

The graphs include, the total cumulative loss of both the STM and EEM in per unit, the associated secondary ohmics loss (rotor loss) in per unit, the percent increase in rotor loss in percentage, the associated primary ohmics loss (stator loss) in per unit, the percent increase in stator loss in percentage, the efficiencies of EEM and STM in percentage, percentage decrease in efficiencies for each motor, the yearly savings (\$), percent increase in yearly savings in percentage and the payback period in year(s).

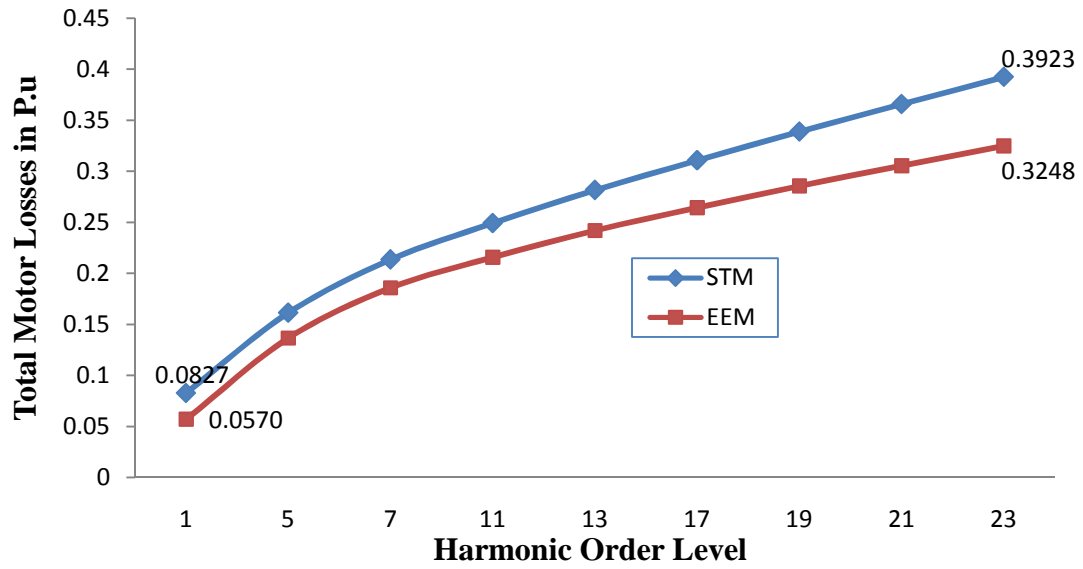


Figure 4.1: Cummulative Total Losses for 25HP Motors

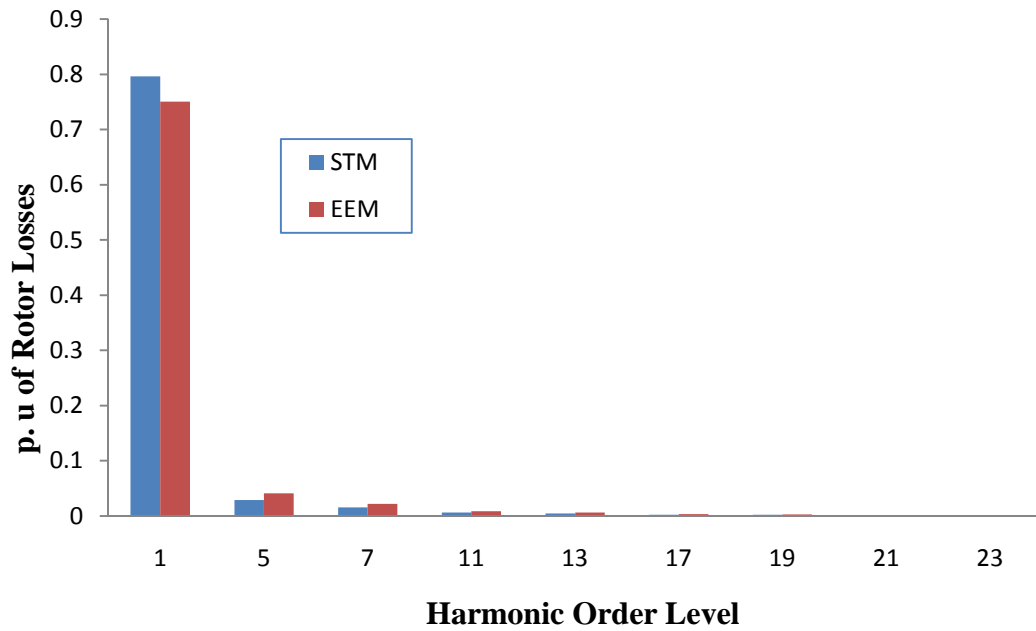


Figure 4.2: Rotor Losses for 25HP Motors vs. Harmonic Order Level

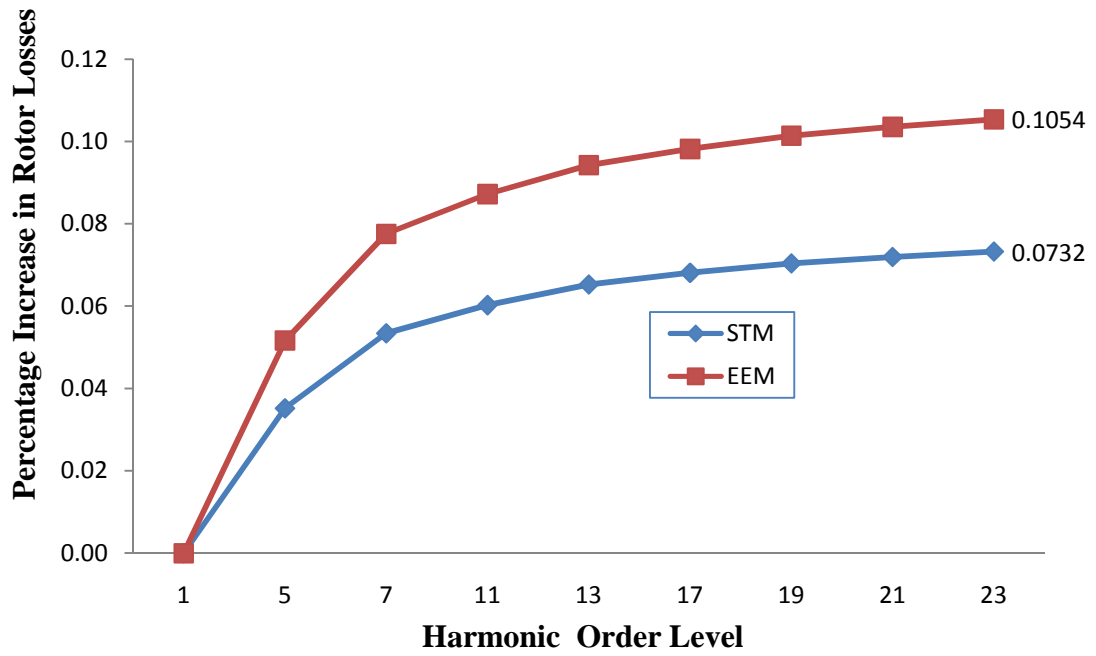


Figure 4.3: Percent Increase in Rotor Losses for 25 HP Motors vs. Harmonic Order Level

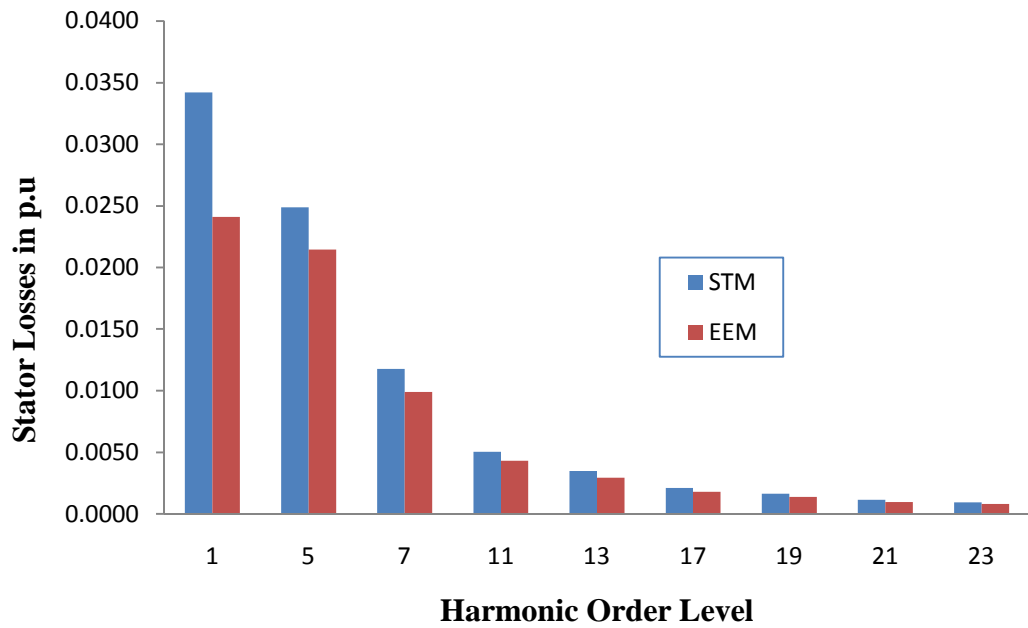


Figure 4.4: Stator Losses for 25 HP Motors vs. Harmonic Order Level

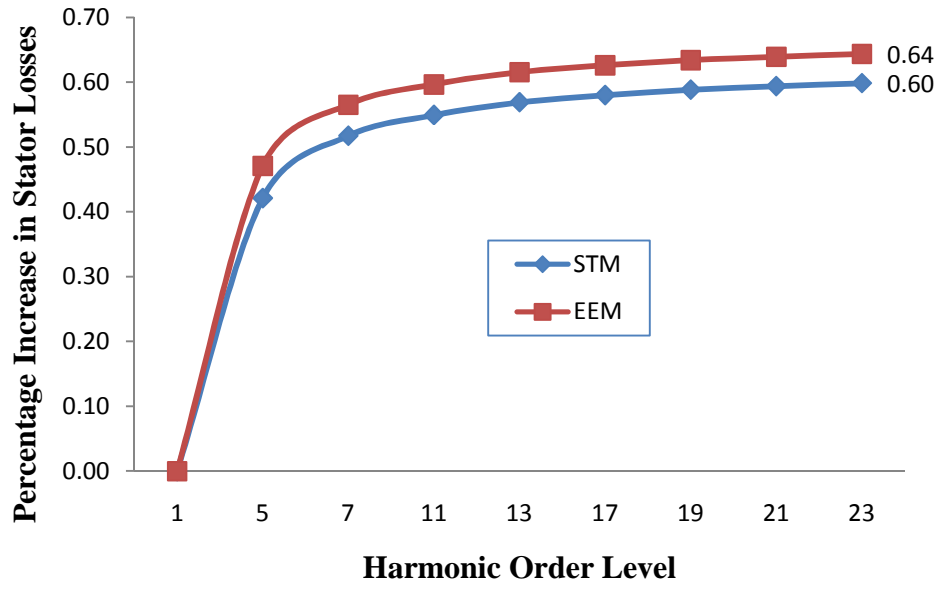


Figure 4.5: Percent Increase in Stator Losses for 25HP Motors vs. Harmonic Order Level

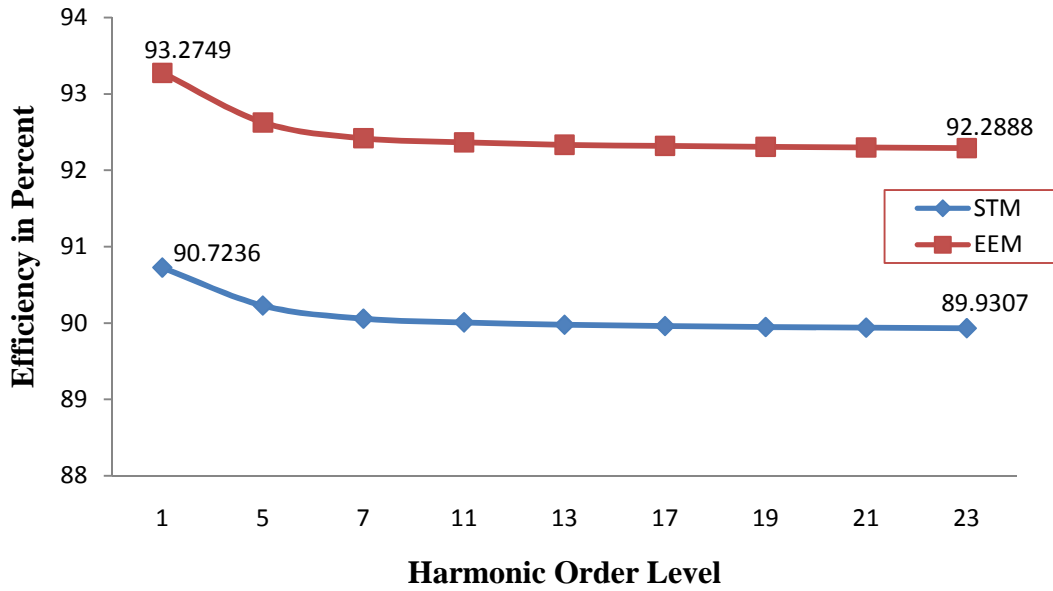


Figure 4.6: Efficiencies for 25 HP Motors vs. Harmonic Order Level

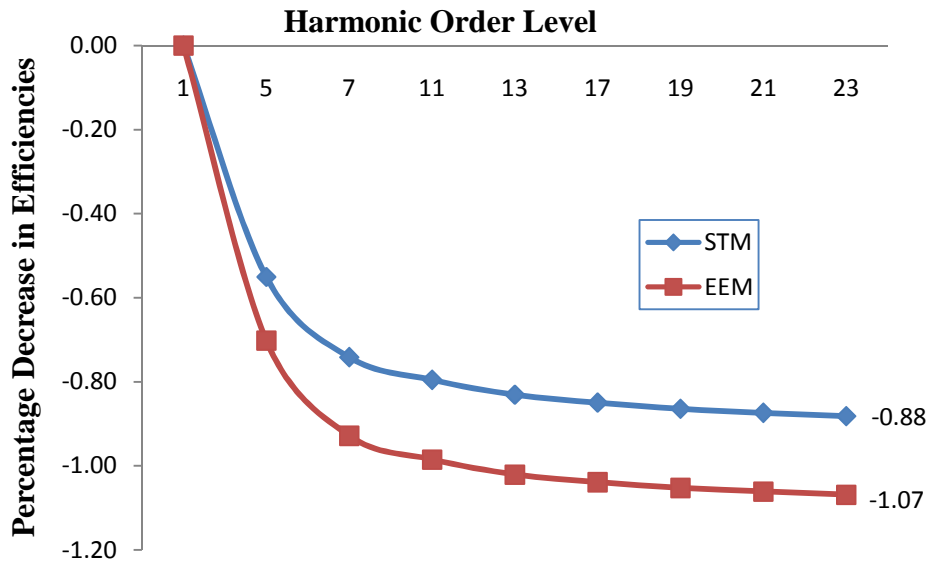


Figure 4.7: Percent Decrease In Efficiencies for 25 HP Motors vs. Harmonic Order Level

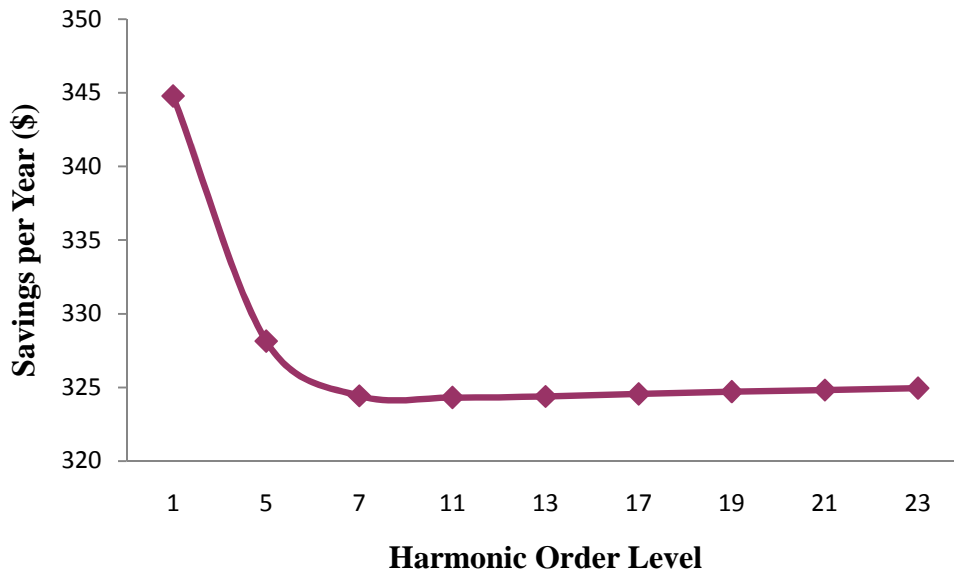


Figure 4.8: Yearly Savings for 25 HP EEM over STM vs. Harmonic Order Level

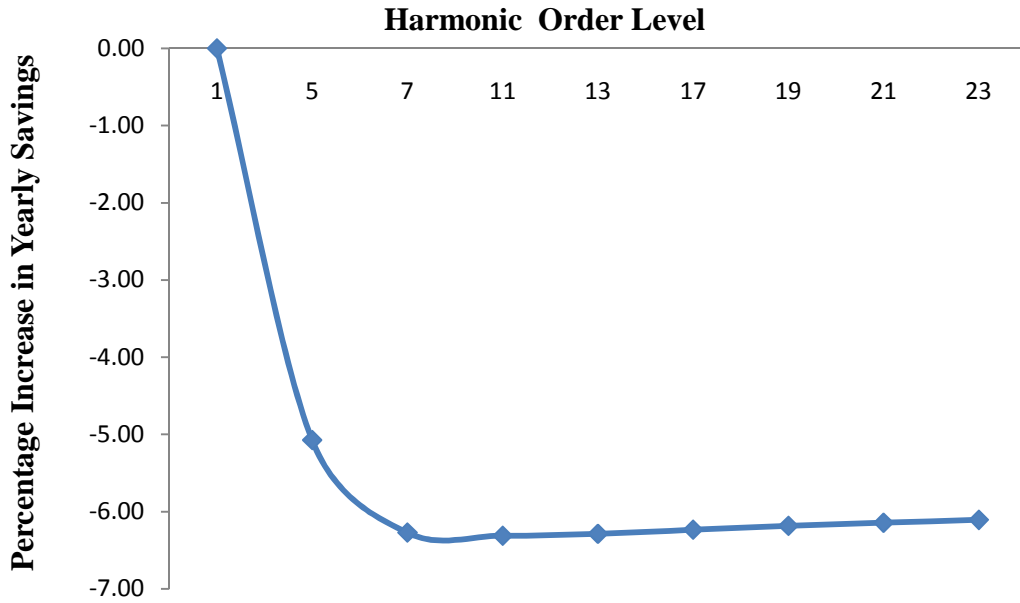


Figure 4.9: Percent Increase in Yearly Savings for 25 HP EEM over STM vs. Harmonic Order Level

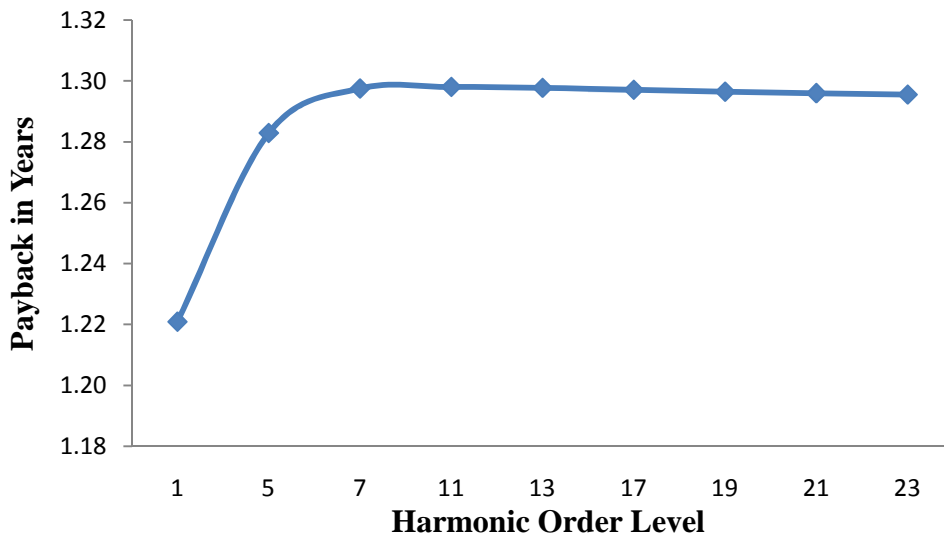


Figure 4.10: Payback Time for 25 HP Motors vs. Harmonic Order Level

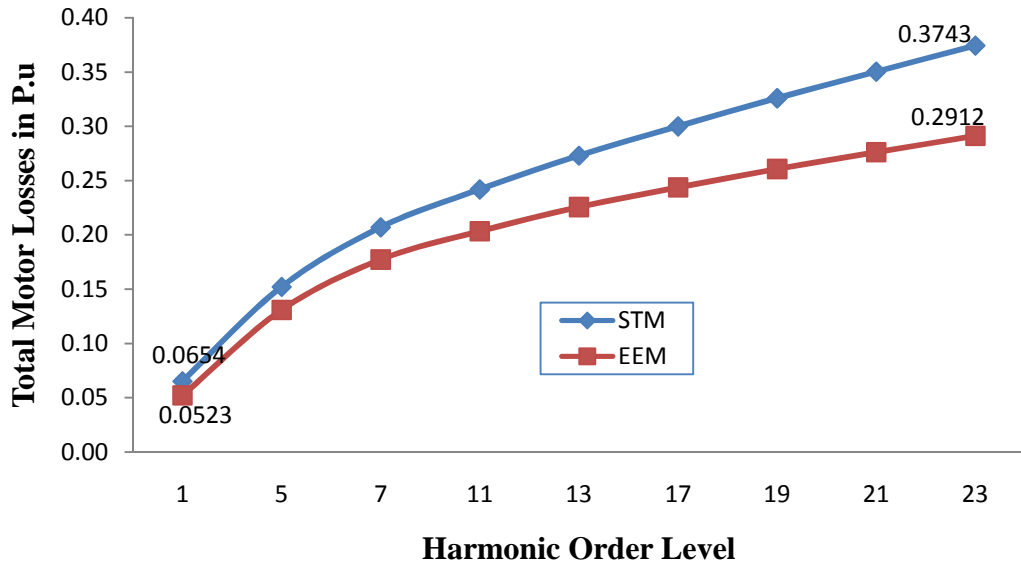


Figure 4.11: Cummulative Total Losses for 50HP Motors

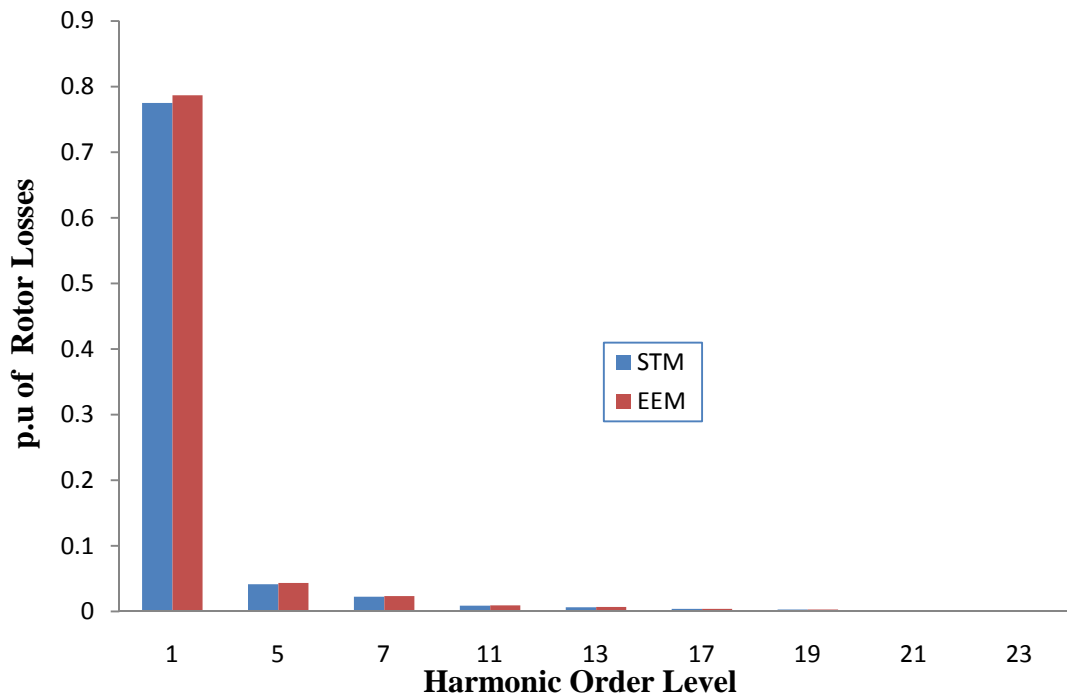


Figure 4.12: Rotor Losses for 50HP Motors vs. Harmonic Order Level

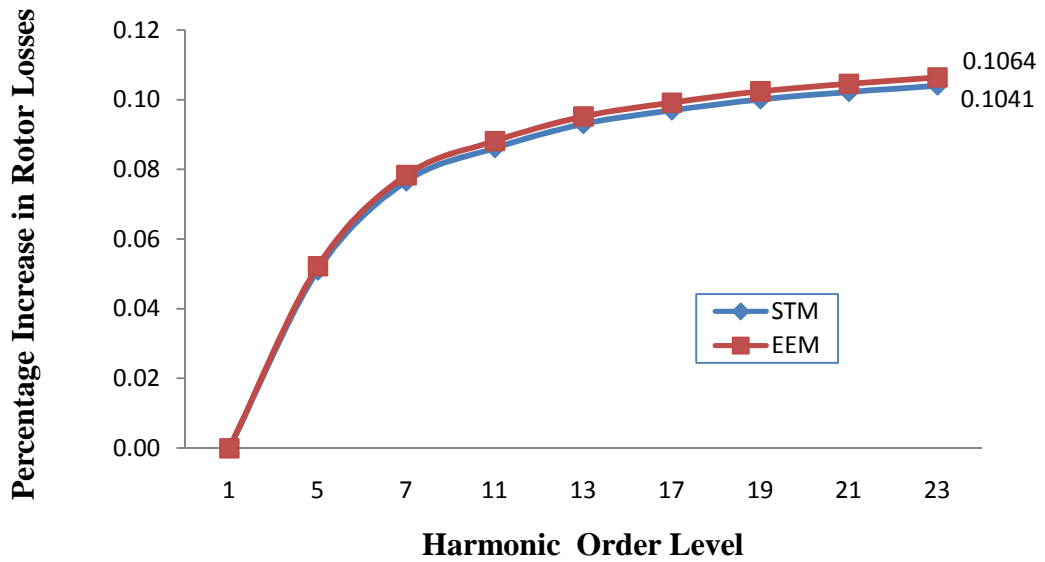


Figure 4.13: Percent Increase in Rotor Losses for 50 HP Motors vs. Harmonic Order Level

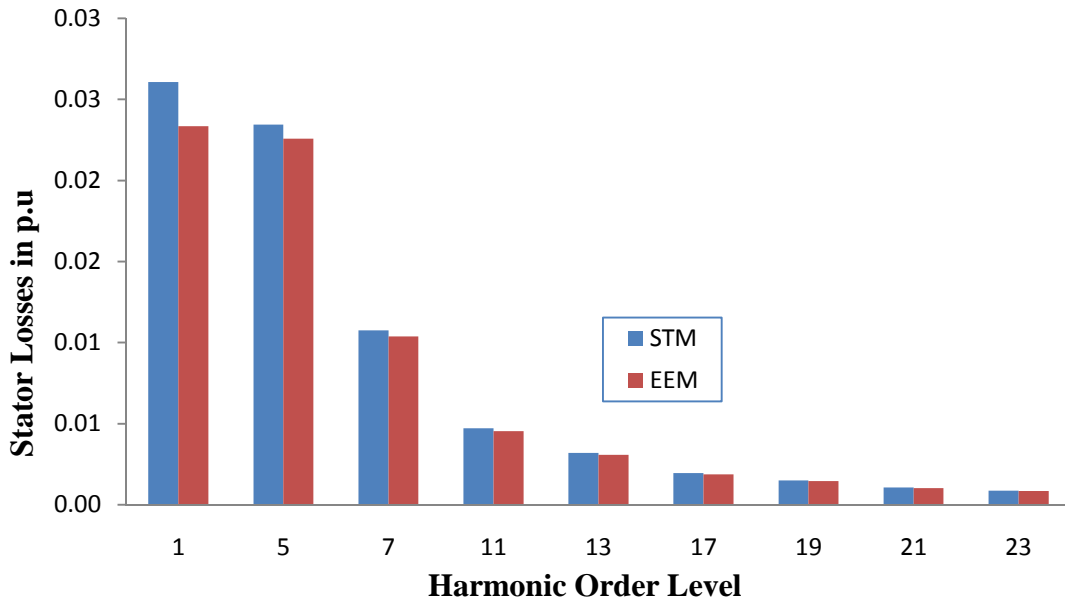


Figure 4.14: Stator Losses for 50 HP Motors vs. Harmonic Order Level

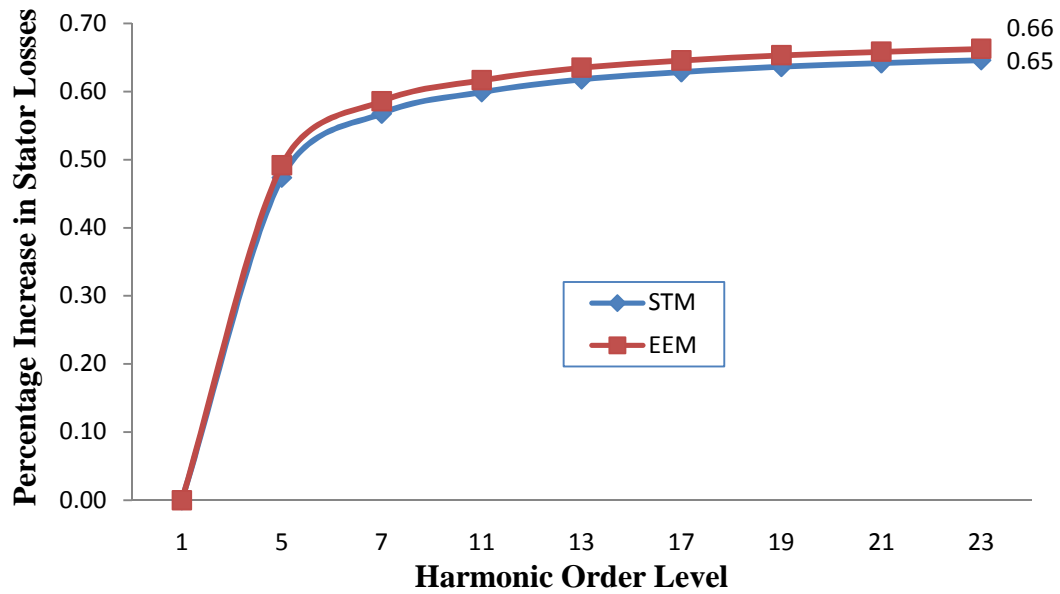


Figure 4.15: Percent Increase in Stator Losses for 50 HP Motors vs. Harmonic Order Level

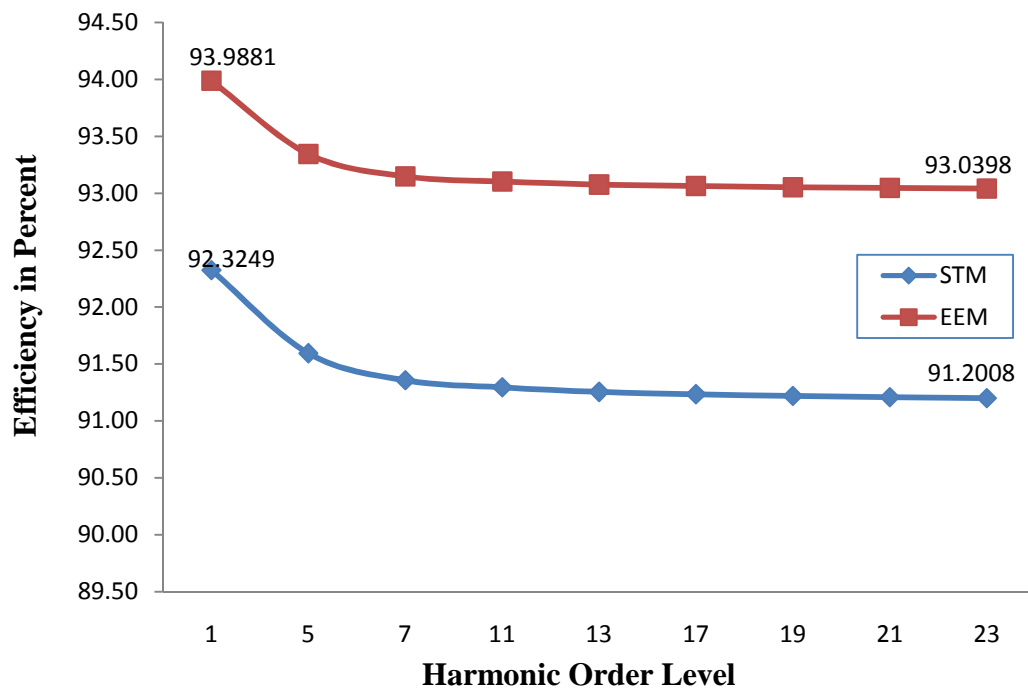


Figure 4.16: Efficiencies for 50 HP Motors vs. Harmonic Order Level

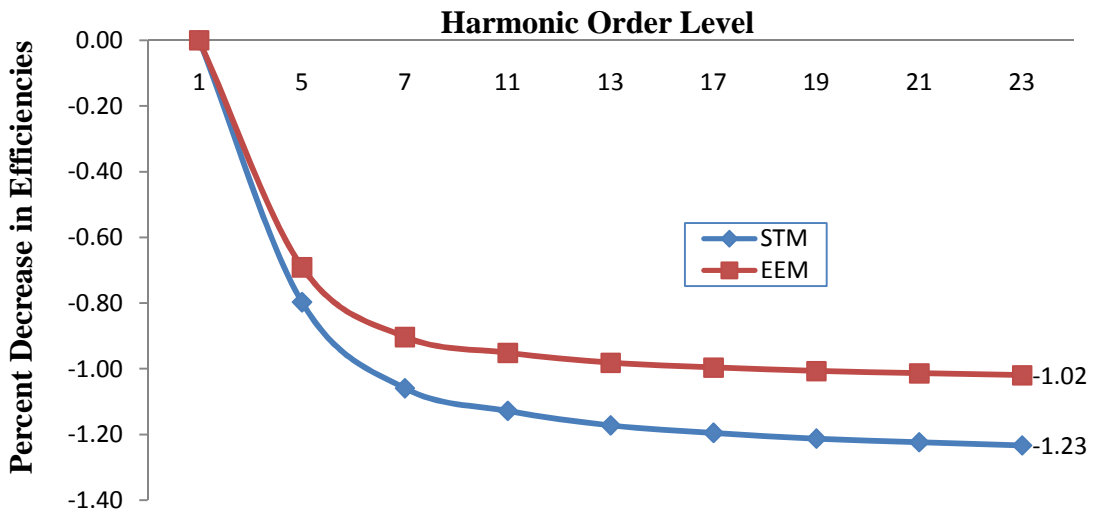


Figure 4.17: Percent Decrease In Efficiencies for 50 HP Motors vs. Harmonic Order Level

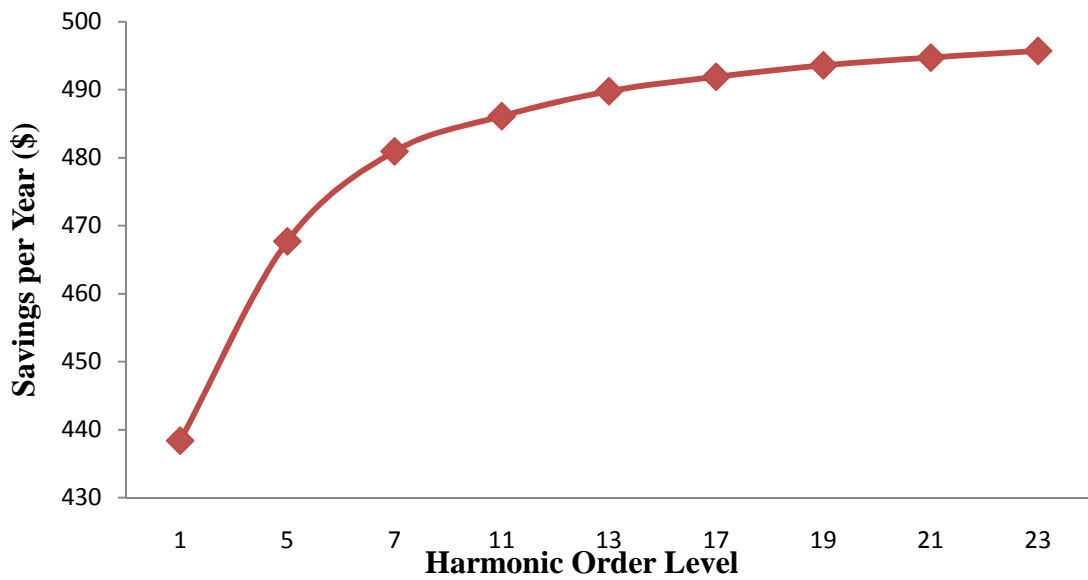


Figure 4.18: Yearly Savings for 50 HP EEM over STM vs. Harmonic Order Level

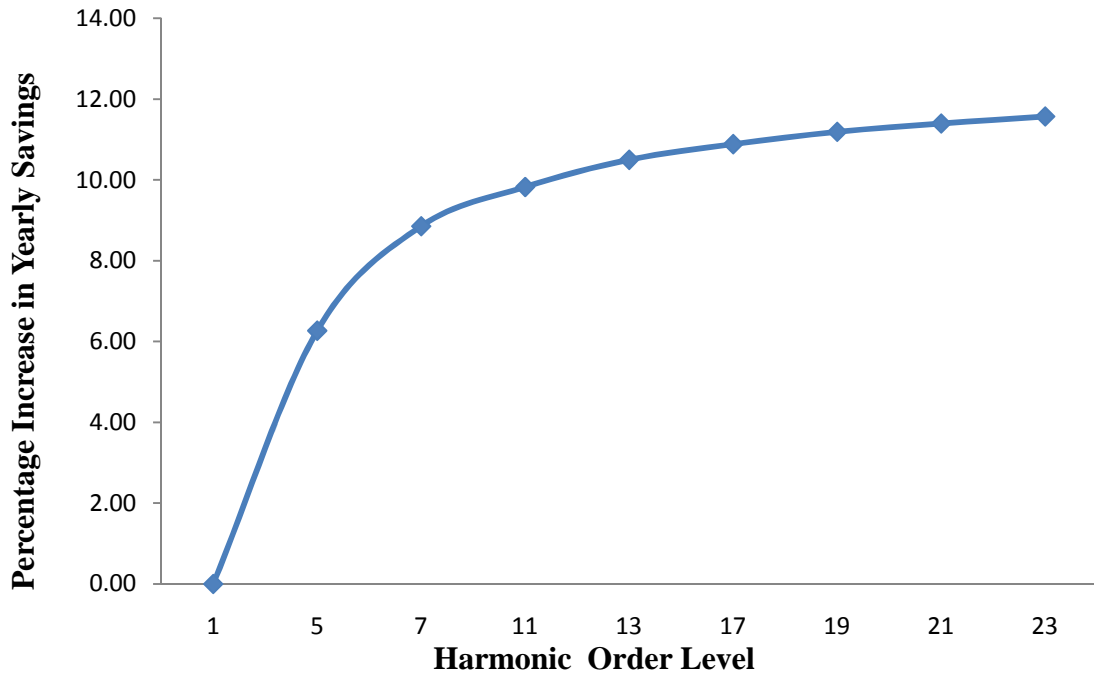


Figure 4.19: Percent Increase in Yearly Savings for 50 HP EEM over STM vs. Harmonic Order Level

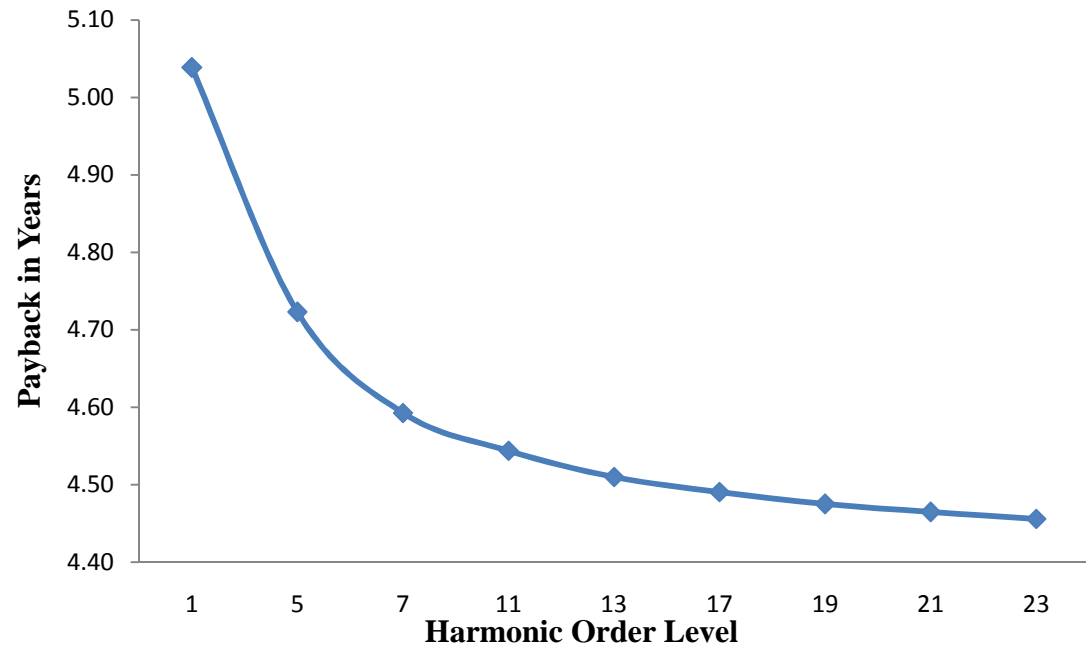


Figure 4.20: Payback Time for 50 HP Motors vs. Harmonic Order Level

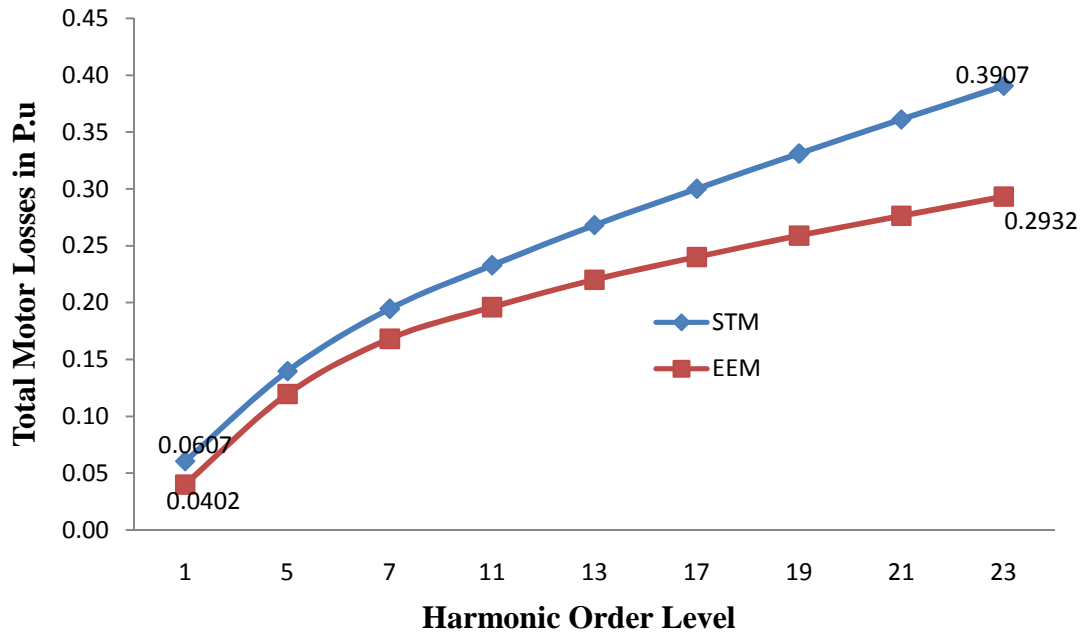


Figure 4.21: Cummulative Total Losses for 100HP Motors

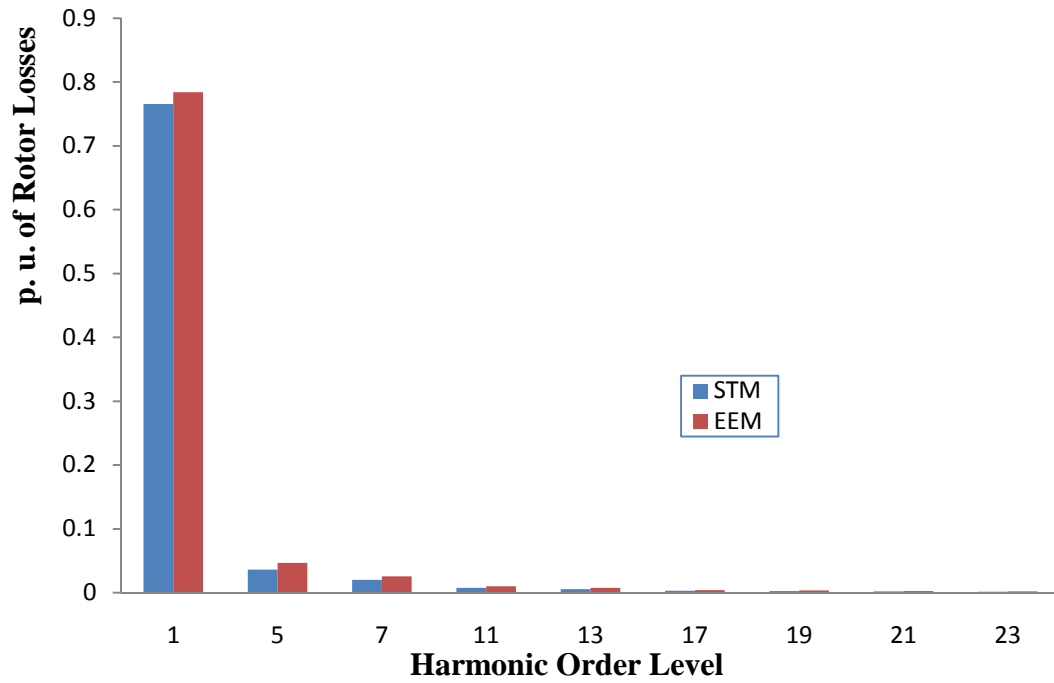


Figure 4.22: Rotor Losses for 100HP Motors vs. Harmonic Order Level

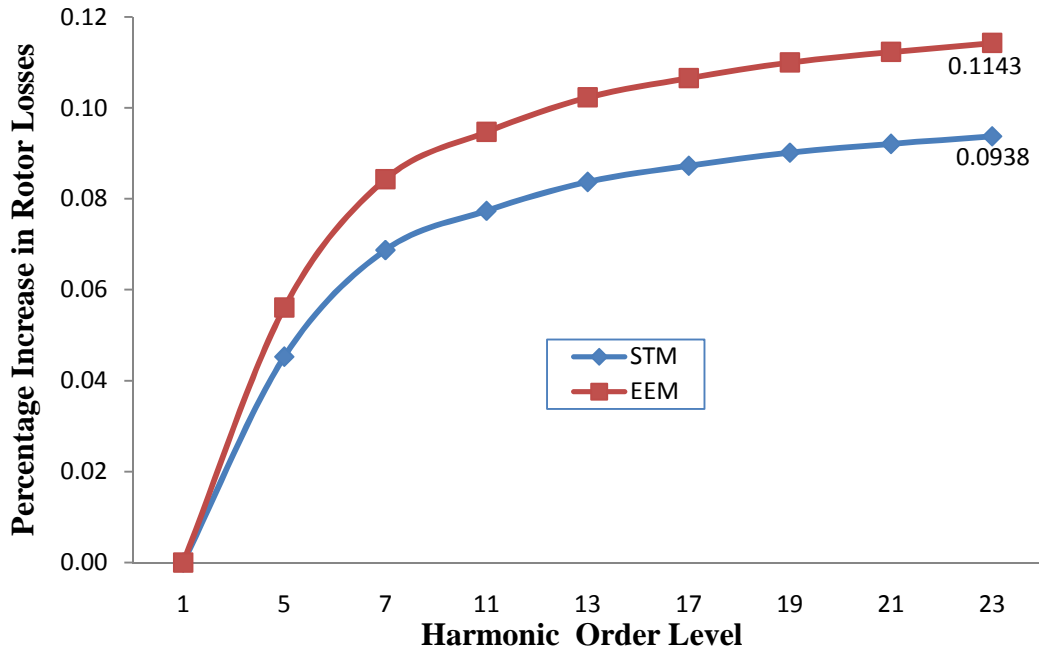


Figure 4.23: Percent Increase in Rotor Losses for 100 HP Motors vs. Harmonic Order Level

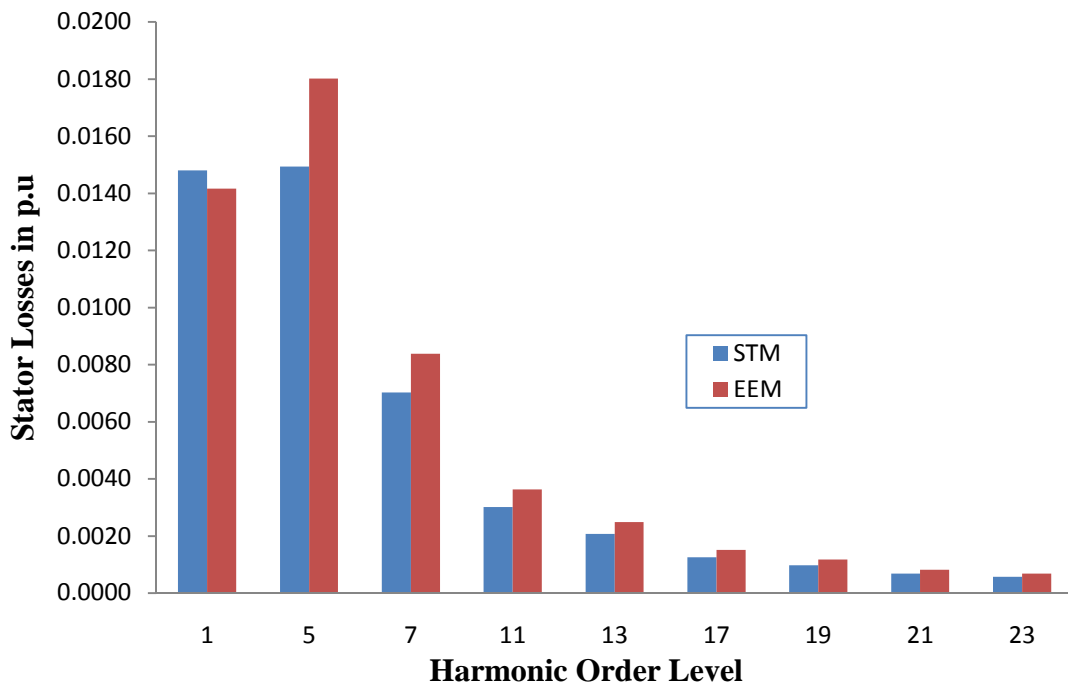


Figure 4.24: Stator Losses for 100 HP Motors vs. Harmonic Order Level

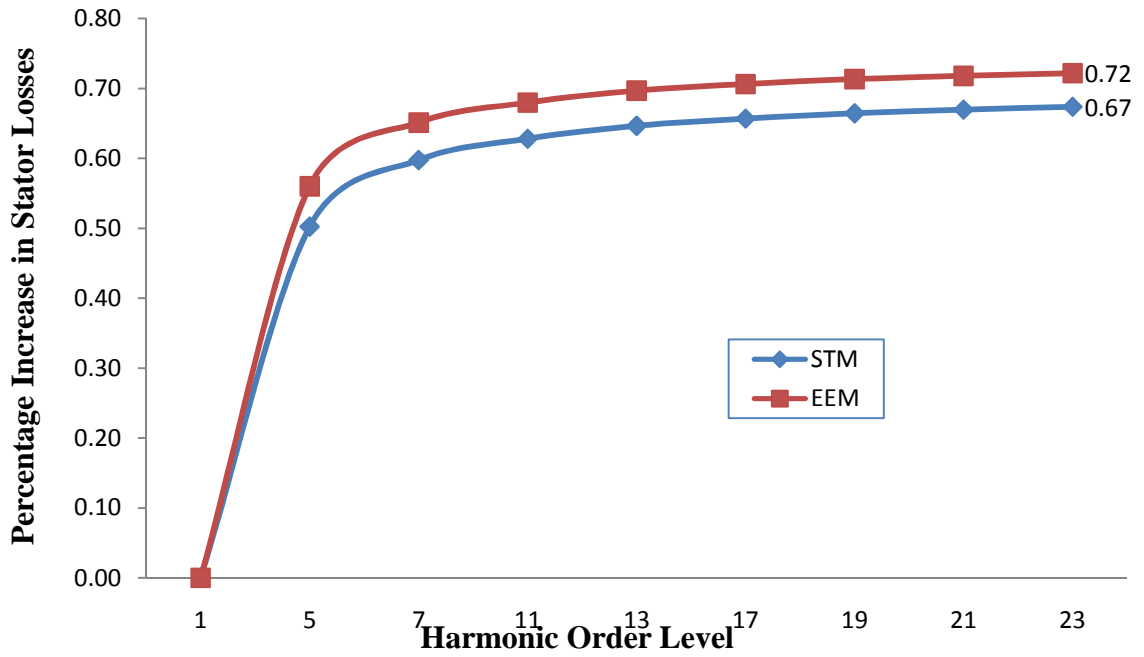


Figure 4.25: Percent Increase in Stator Losses for 100 HP Motors vs. Harmonic Order Level

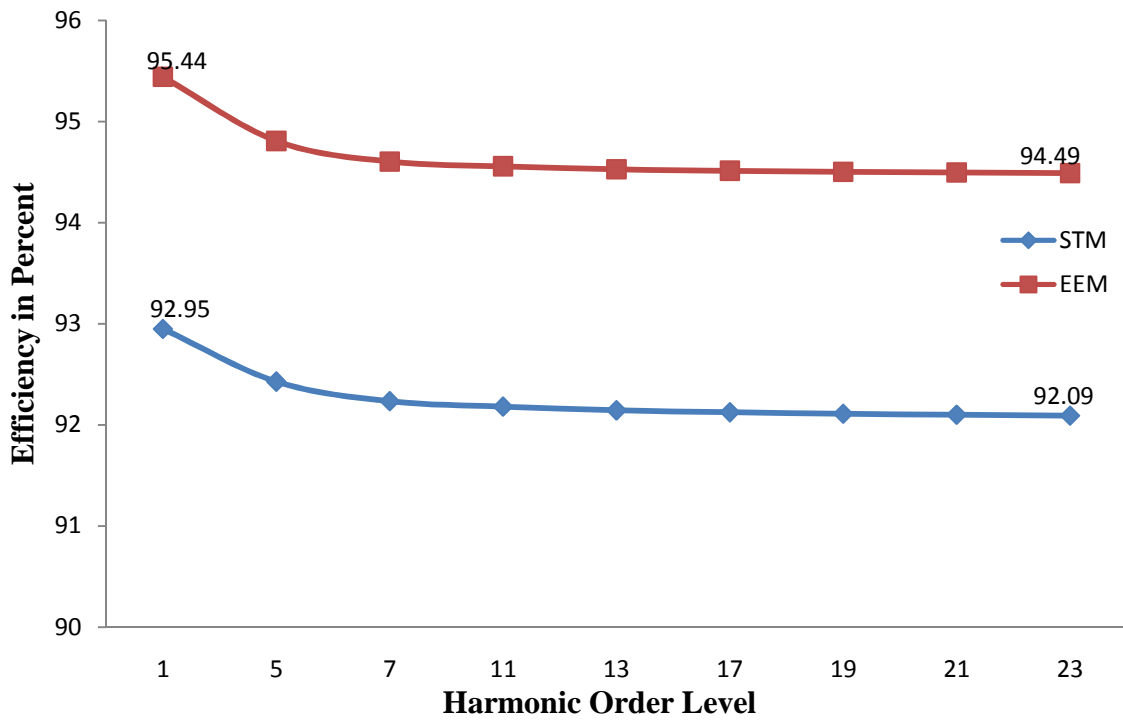


Figure 4.26: Efficiencies for 100 HP Motors vs. Harmonic Order Level

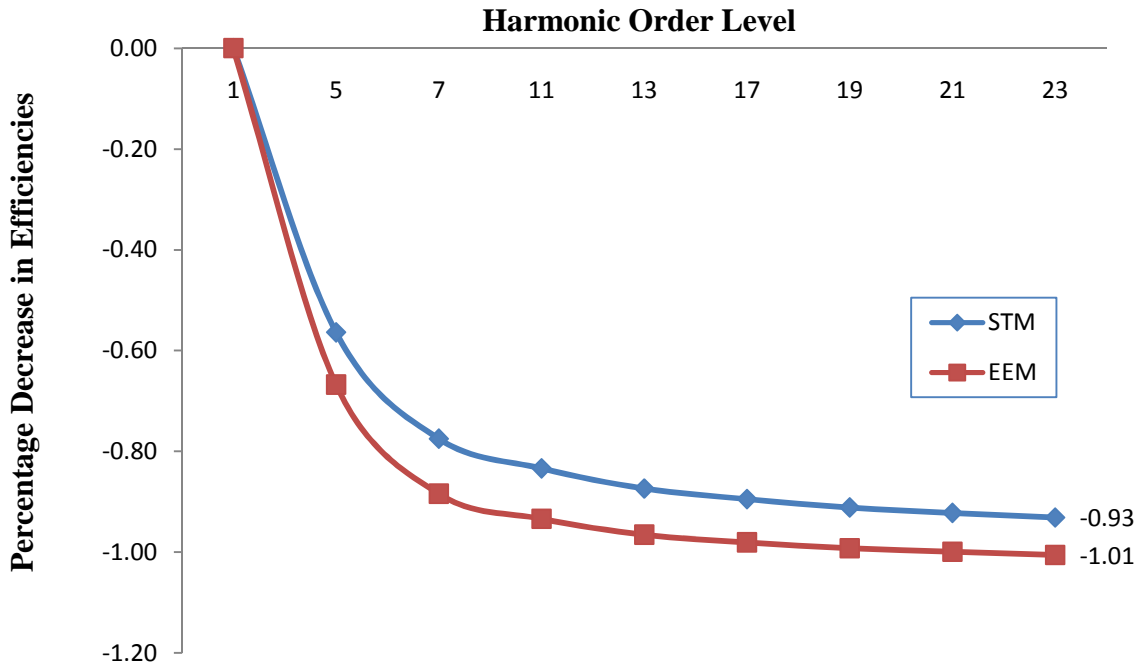


Figure 4.27: Percent Decrease In Efficiencies for 100 HP Motors vs. Harmonic Order Level

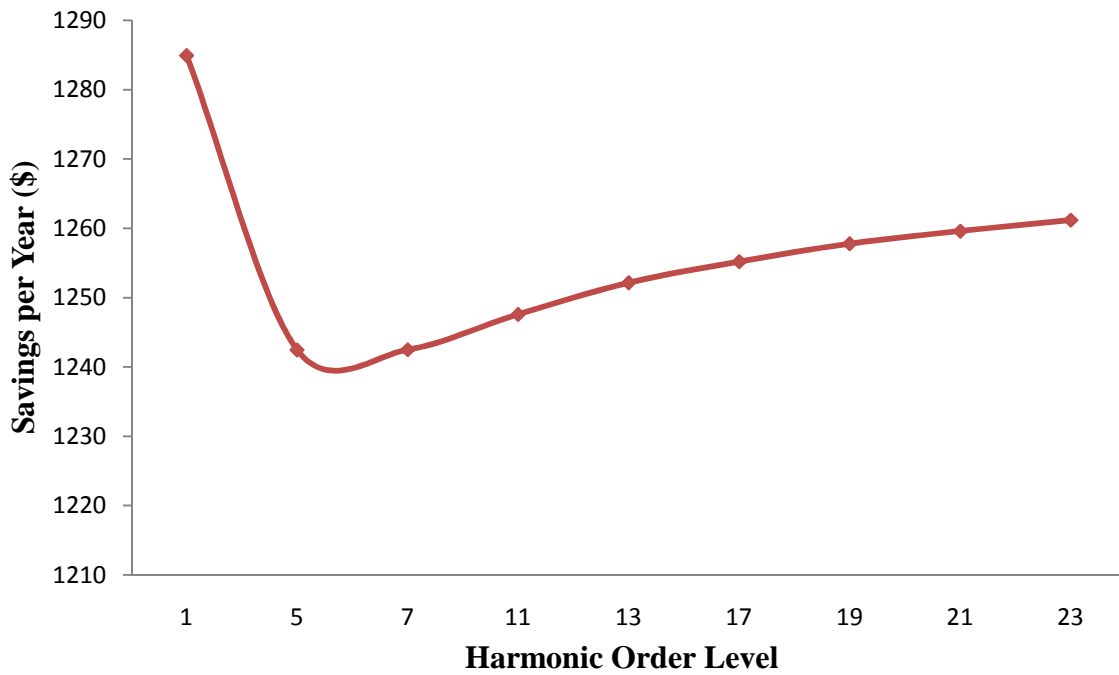


Figure 4.28: Yearly Savings for 100 HP EEM over STM vs. Harmonic Order Level

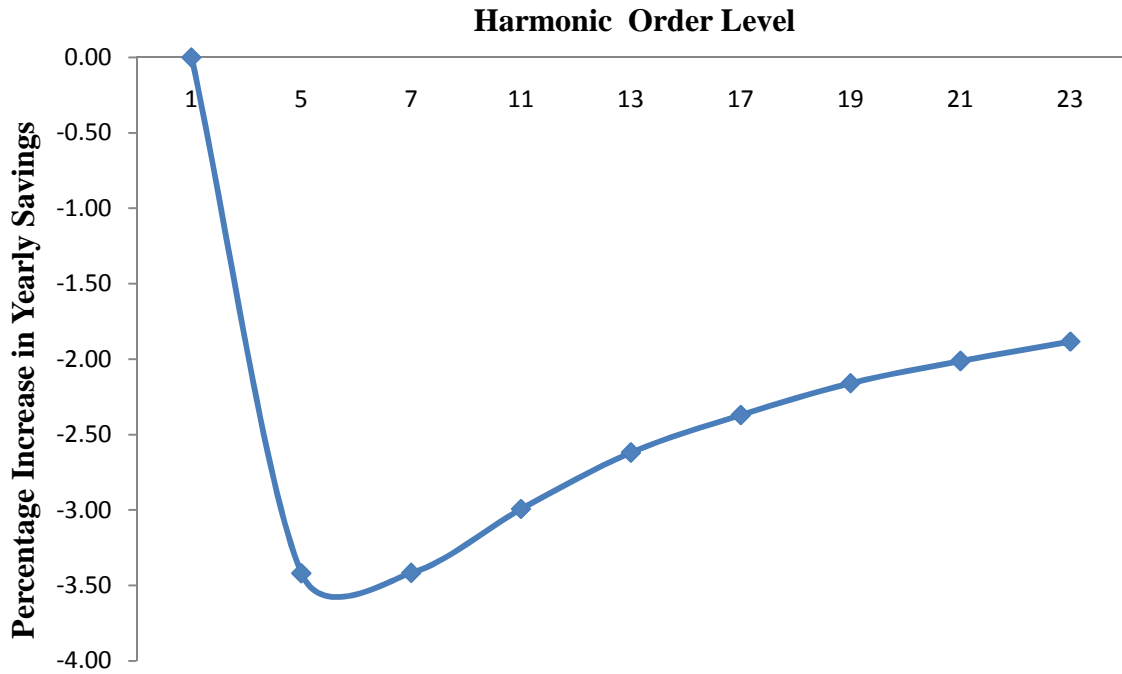


Figure 4.29: Percent Increase in Yearly Savings for 100 HP EEM over STM vs. Harmonic Order Level

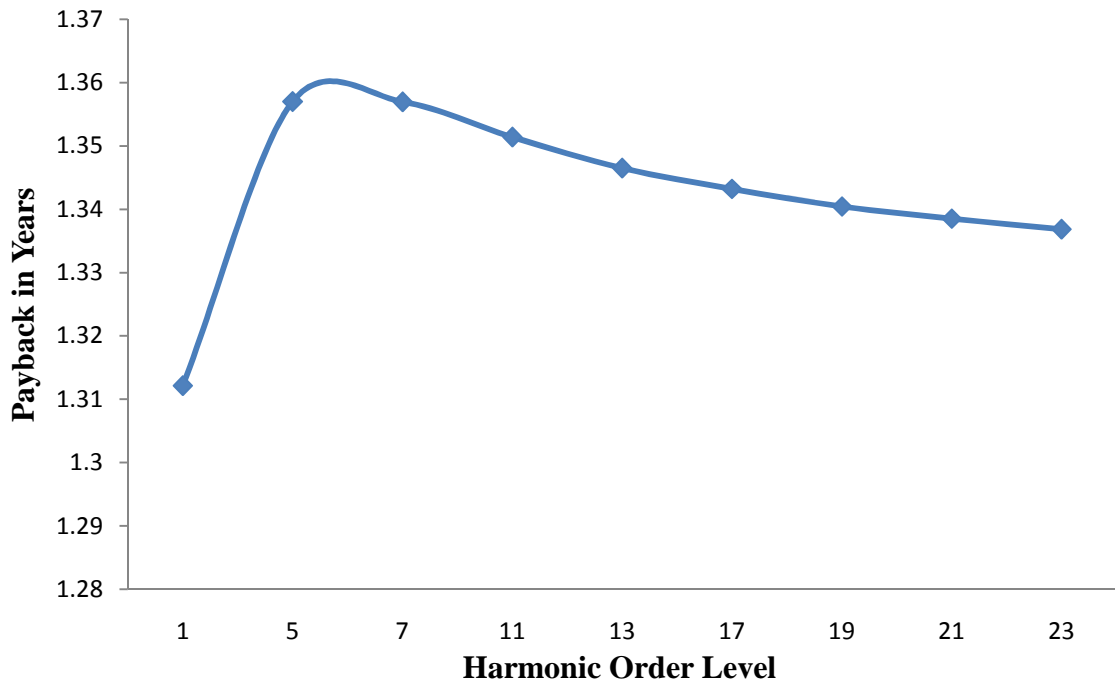


Figure 4.30: Payback Time for 100 HP Motors vs. Harmonic Order Level

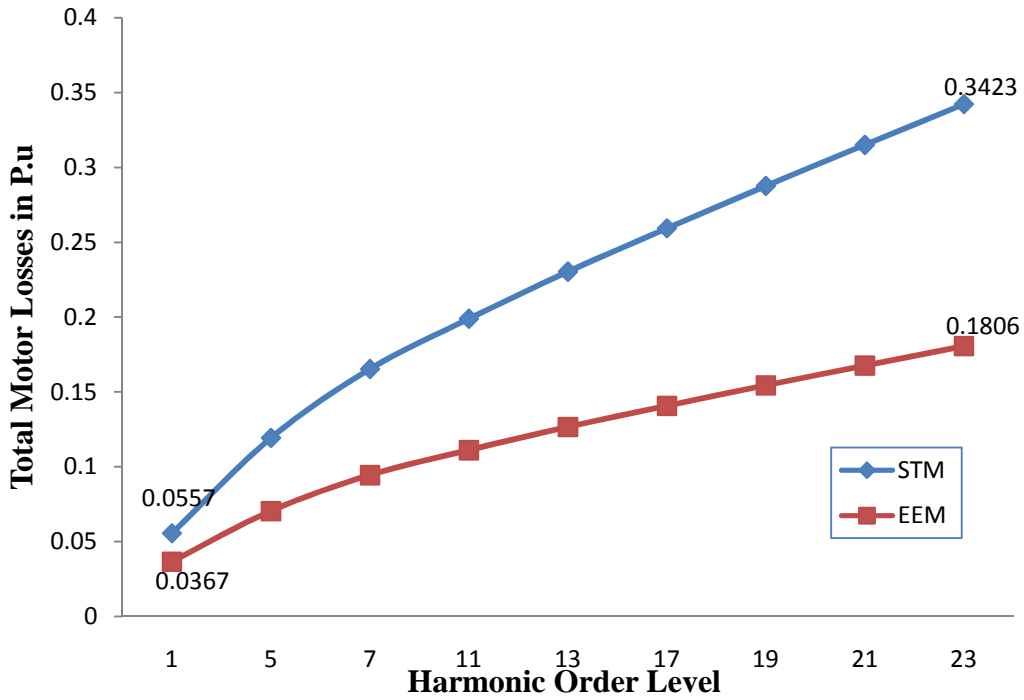


Figure 4.31: Cummulative Total Losses for 150HP Motors

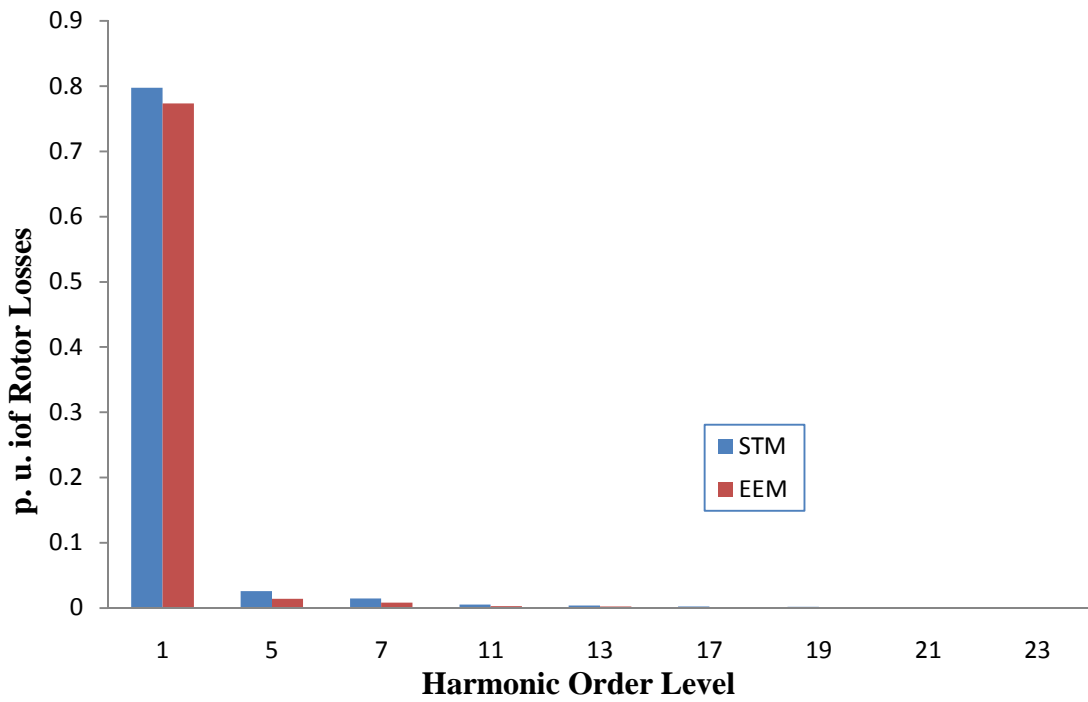


Figure 4.32: Rotor Losses for 150HP Motors vs. Harmonic Order Level

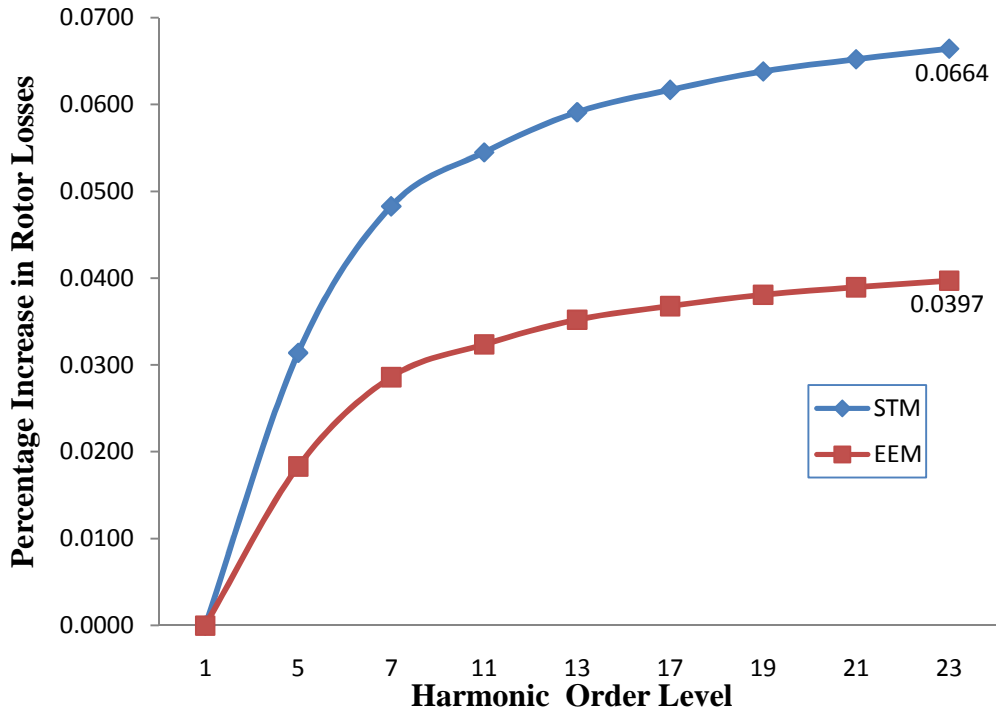


Figure 4.33: Percent Increase in Rotor Losses for 150 HP Motors vs. Harmonic Order Level

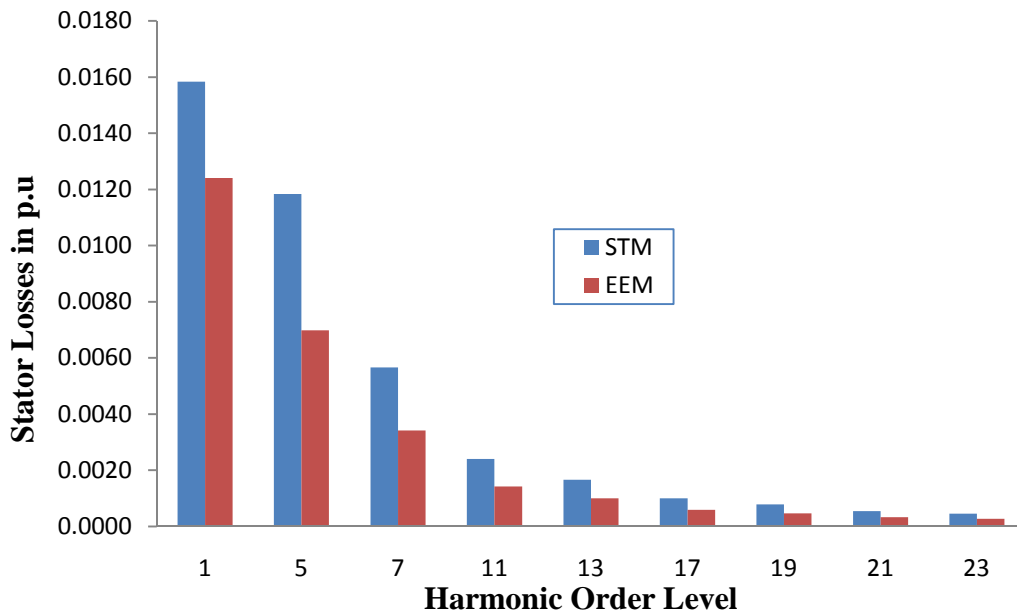


Figure 4.34: Stator Losses for 150 HP Motors vs. Harmonic Order Level

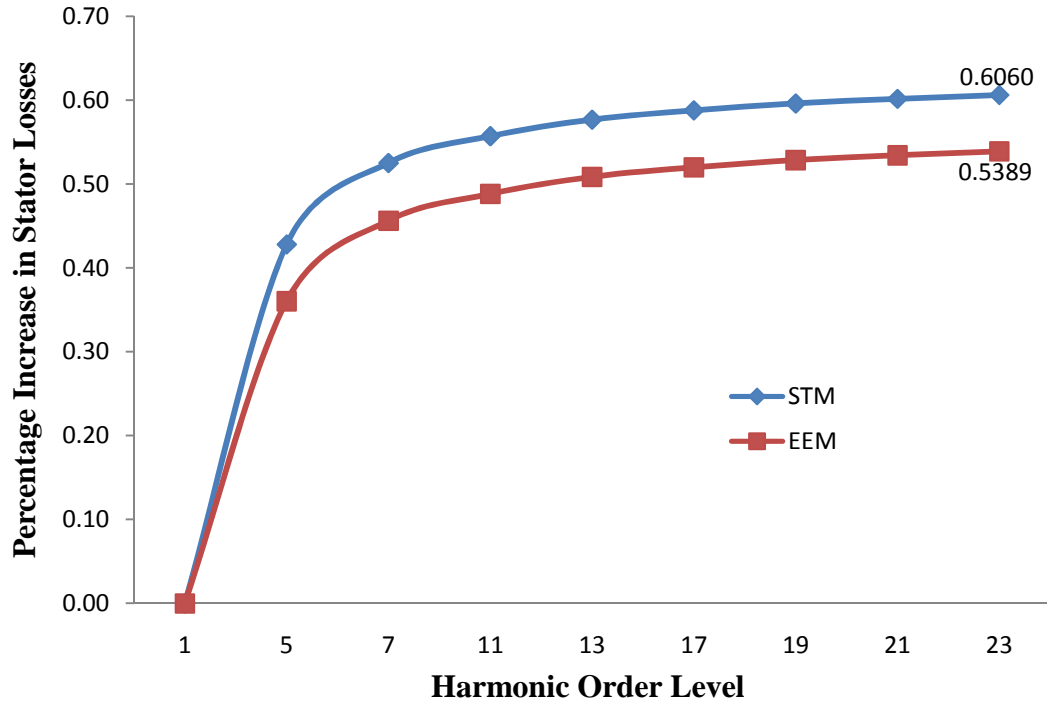


Figure 4.35: Percent Increase in Stator Losses for 150 HP Motors vs. Harmonic Order Level

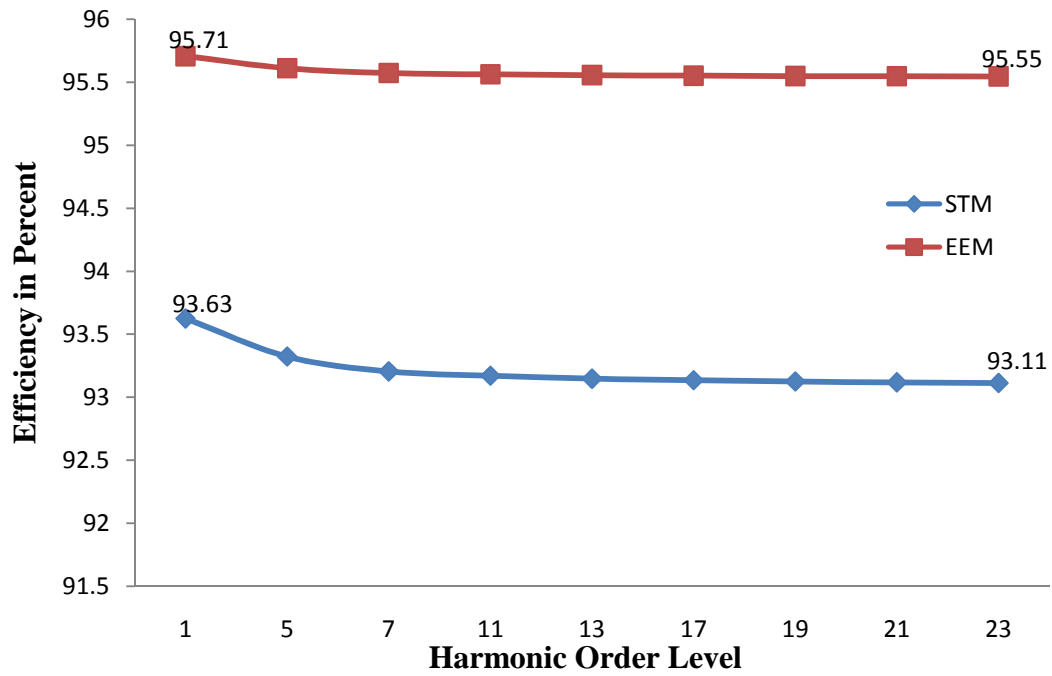


Figure 4.36: Efficiencies for 150 HP Motors vs. Harmonic Order Level

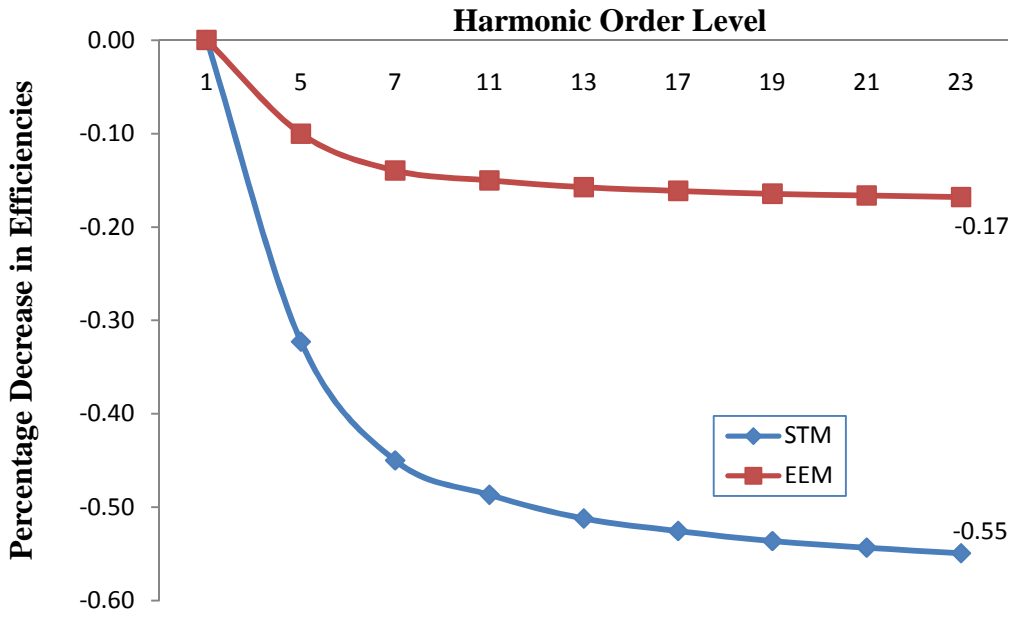


Figure 4.37: Percent Decrease In Efficiencies for 150 HP Motors vs. Harmonic Order Level

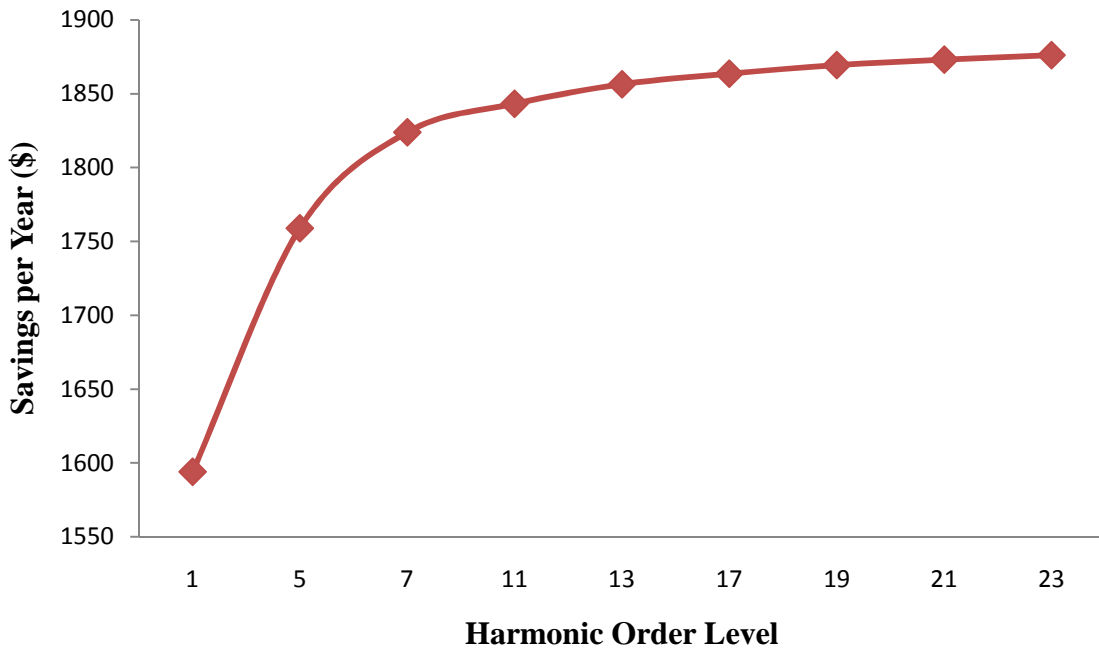


Figure 4.38: Yearly Savings for 150 HP EEM over STM vs. Harmonic Order Level

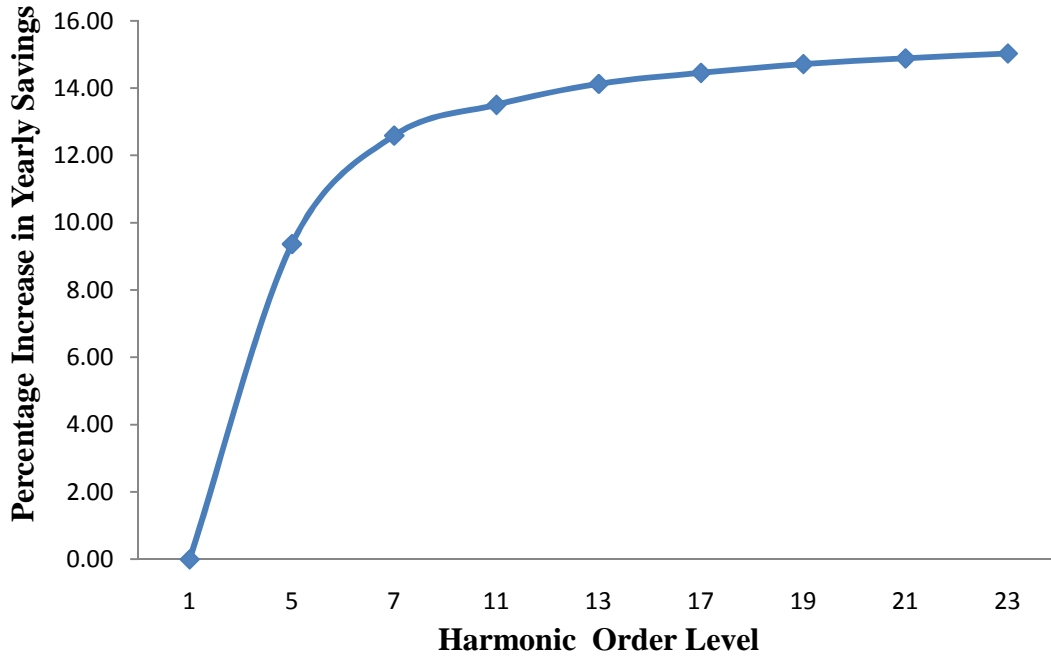


Figure 4.39: Percent Increase in Yearly Savings for 150 HP EEM over STM vs. Harmonic Order Level

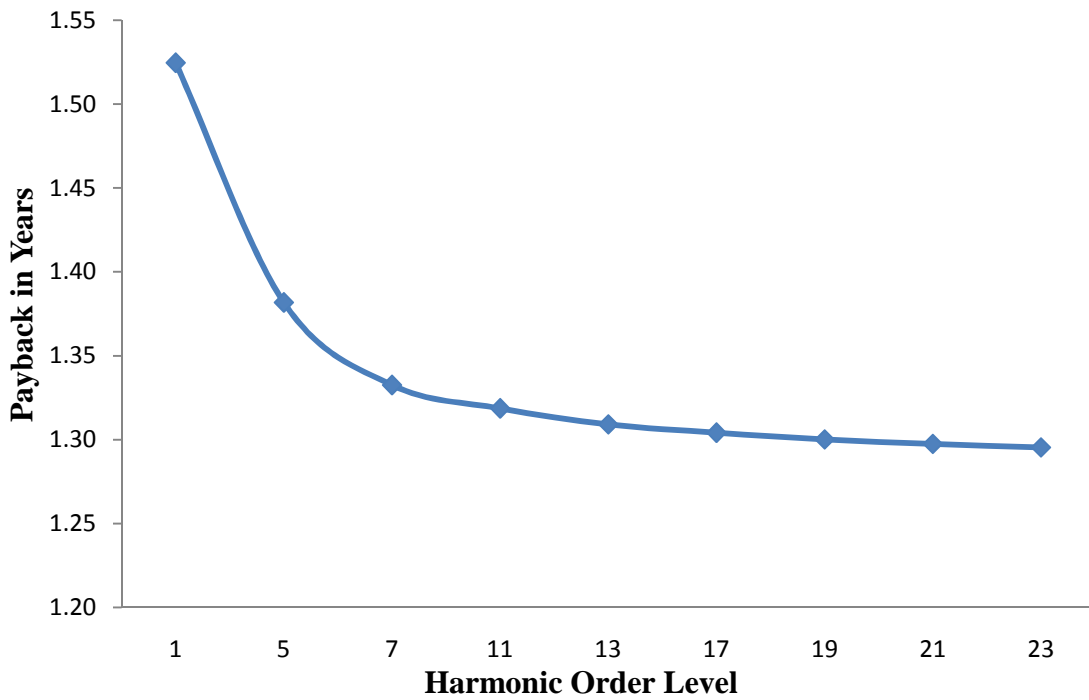


Figure 4.40: Payback Time for 150 HP Motors vs. Harmonic Order Level

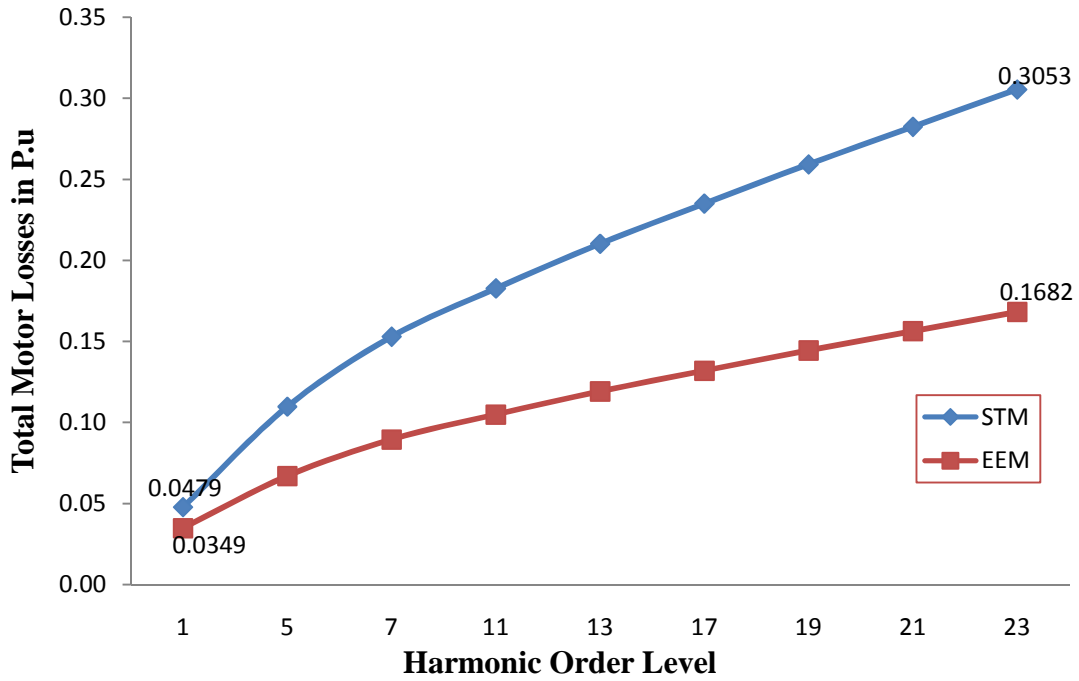


Figure 4.41: Cummulative Total Losses for 200HP Motors

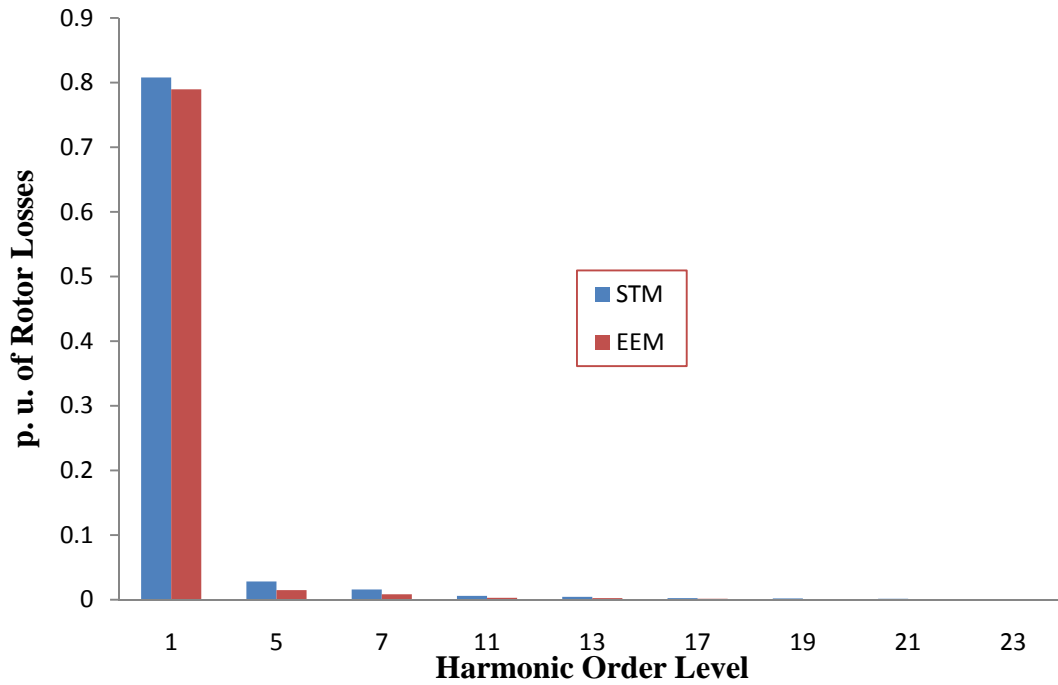


Figure 4.42: Rotor Losses for 200HP Motors vs. Harmonic Order Level

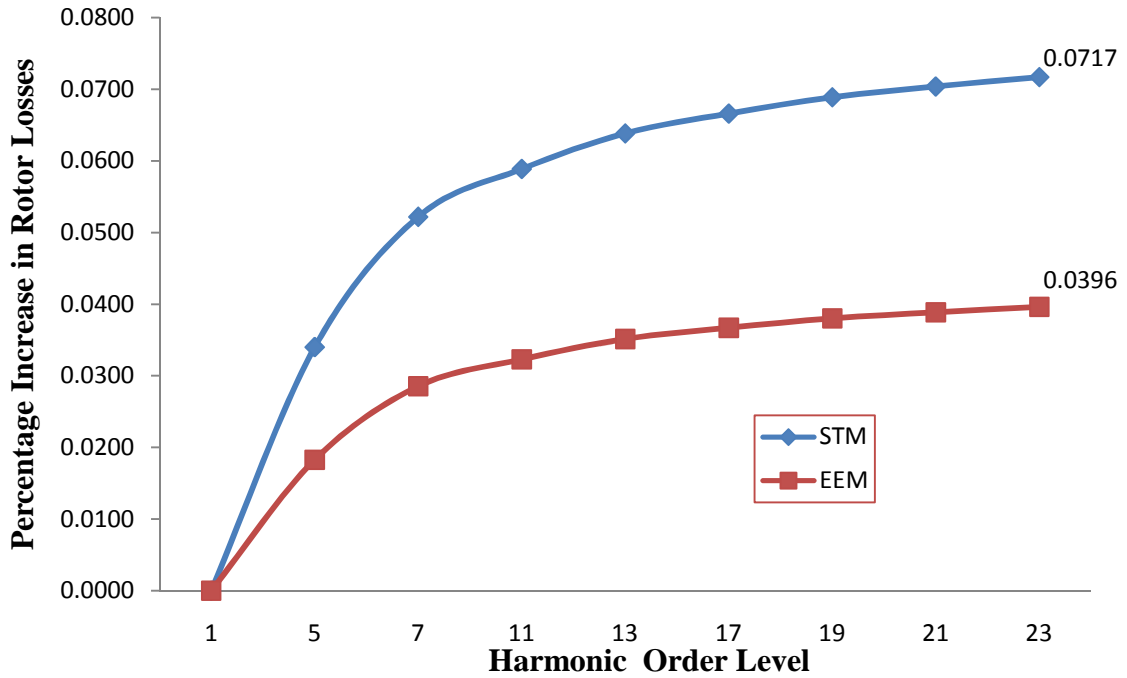


Figure 4.43: Percent Increase in Rotor Losses for 200 HP Motors vs. Harmonic Order Level

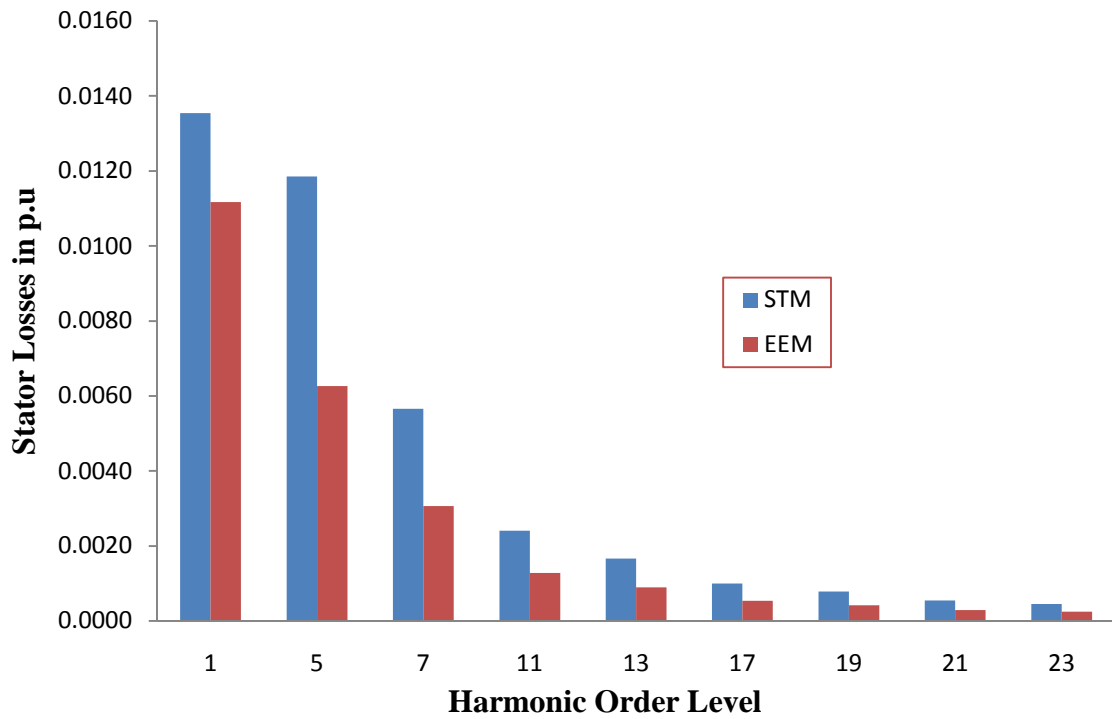


Figure 4.44: Stator Losses for 200 HP Motors vs. Harmonic Order Level

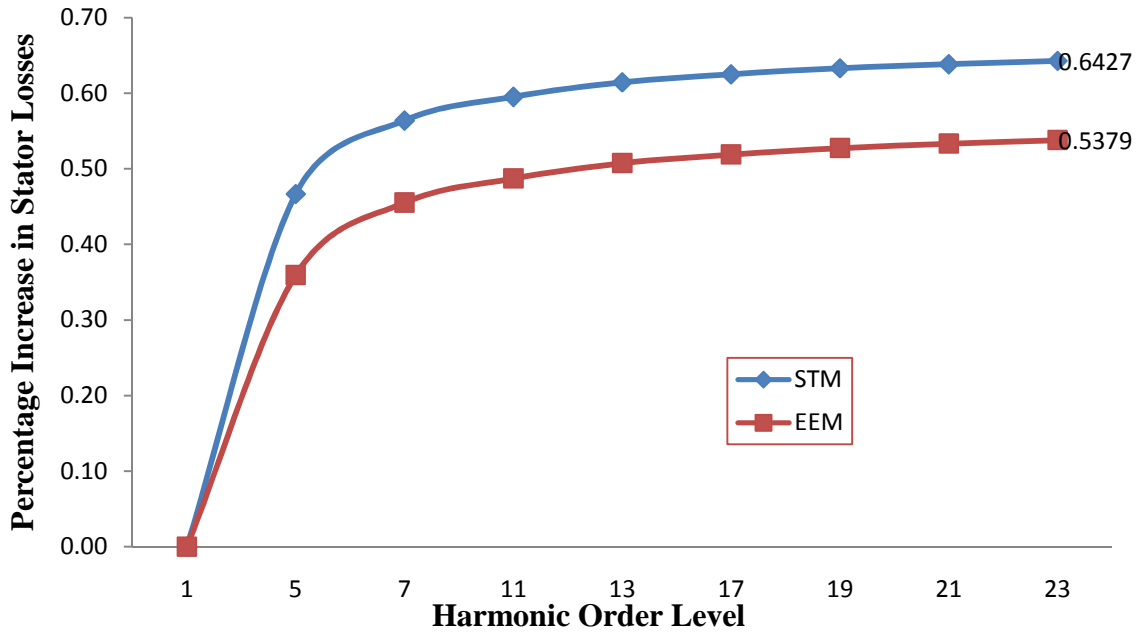


Figure 4.45: Percent Increase in Stator Losses for 200 HP Motors vs. Harmonic Order Level

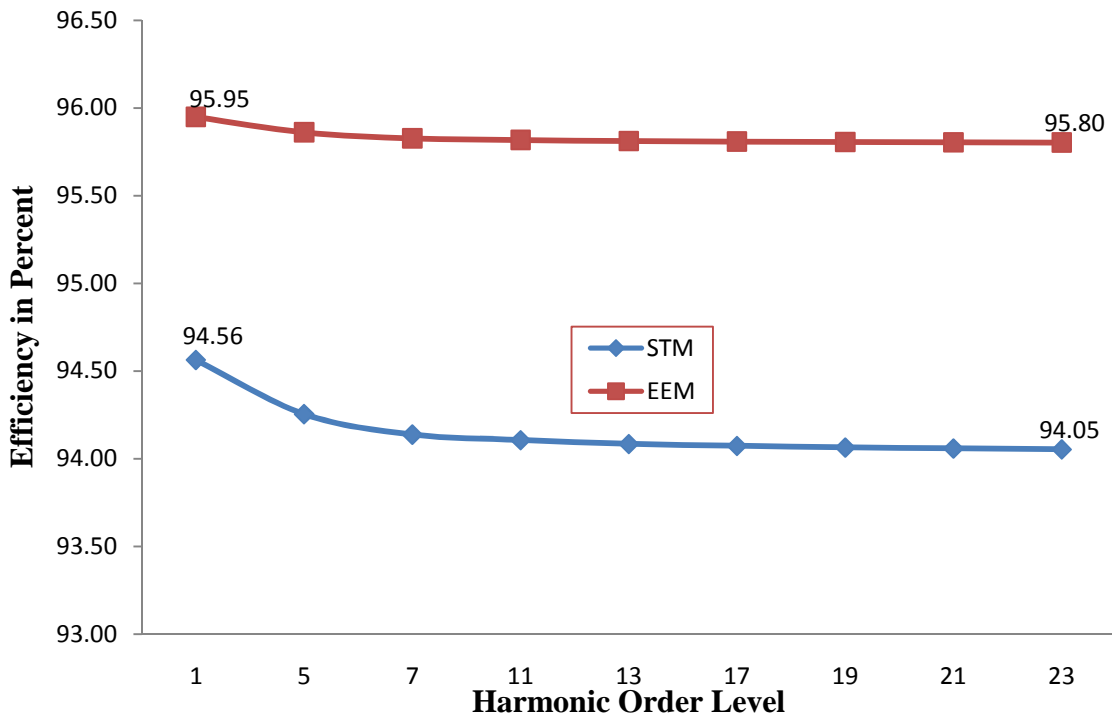


Figure 4.46: Efficiencies for 200 HP Motors vs. Harmonic Order Level

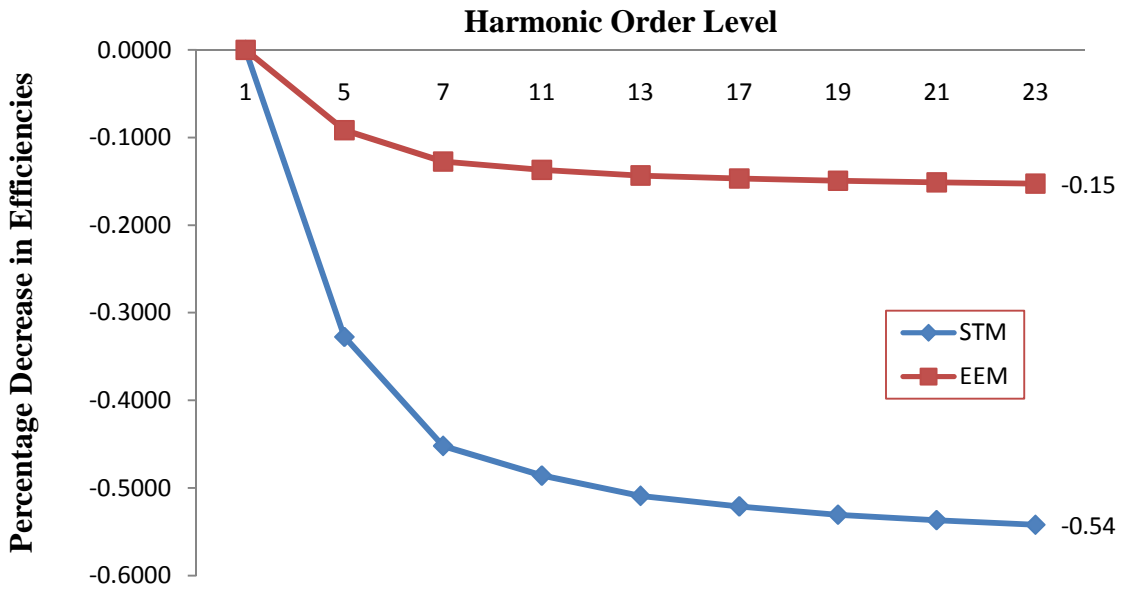


Figure 4.47: Percent Decrease In Efficiencies for 200HP Motors vs. Harmonic Order Level

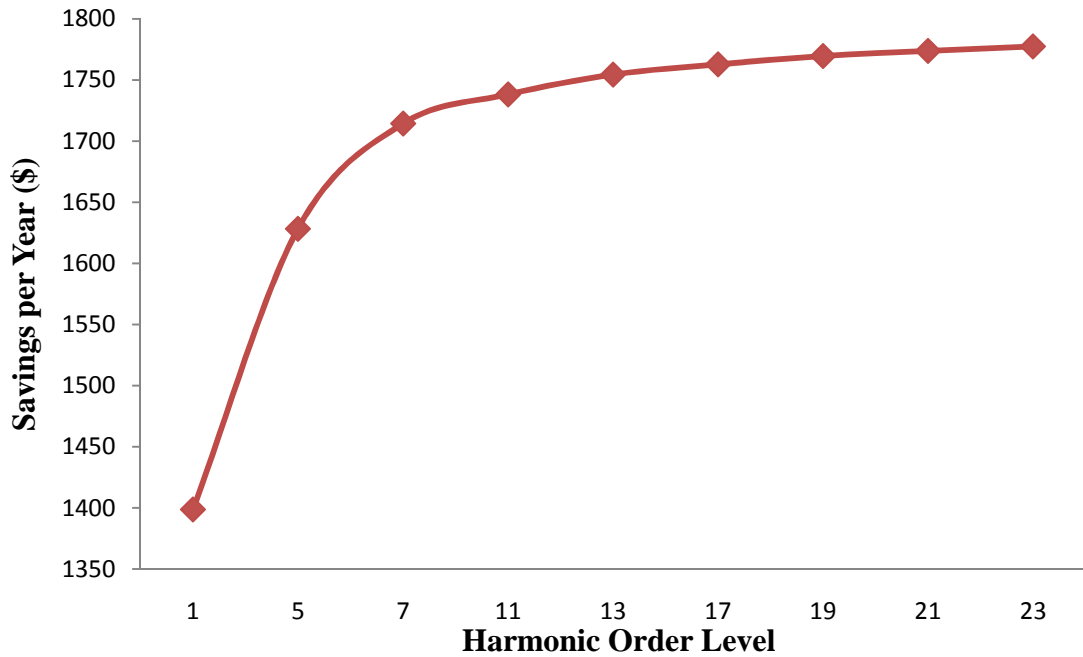


Figure 4.48: Yearly Savings for 200 HP EEM over STM vs. Harmonic Order Level

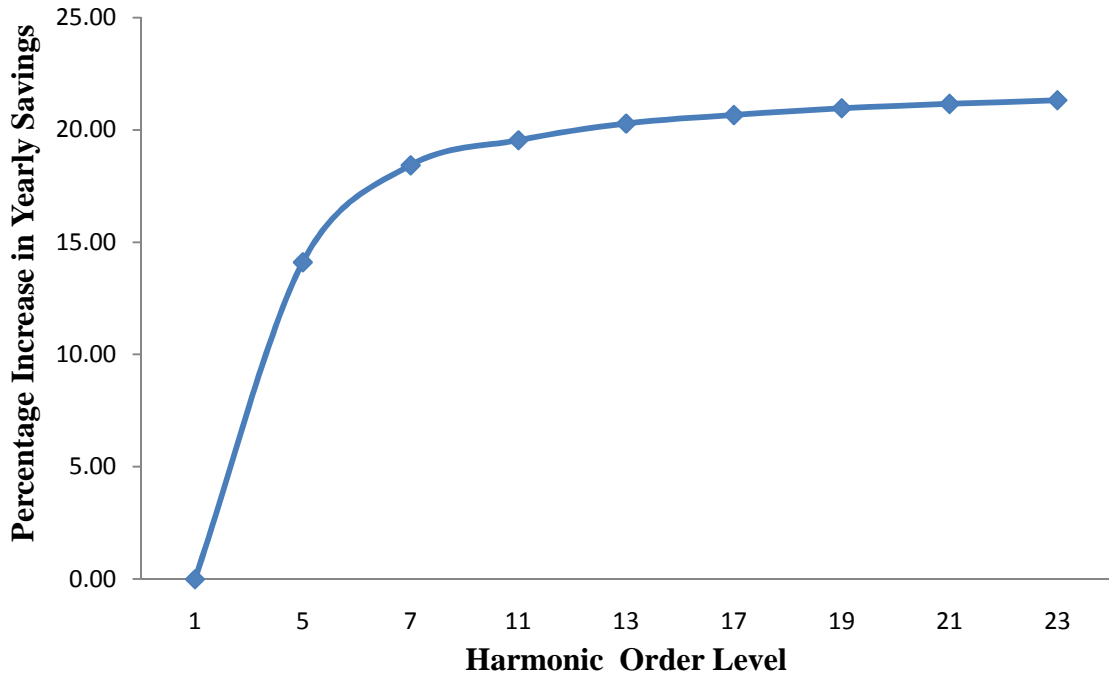


Figure 4.49: Percent Increase in Yearly Savings for 200 HP EEM over STM vs. Harmonic Order Level

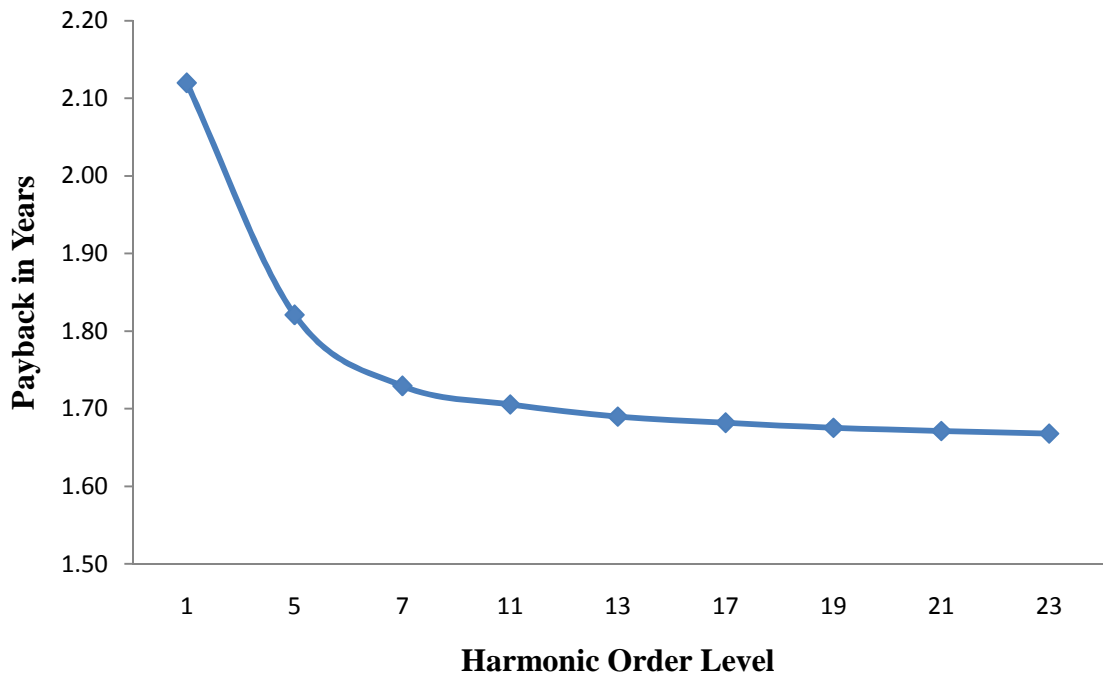


Figure 4.50: Payback Time for 200 HP Motors vs. Harmonic Order Level

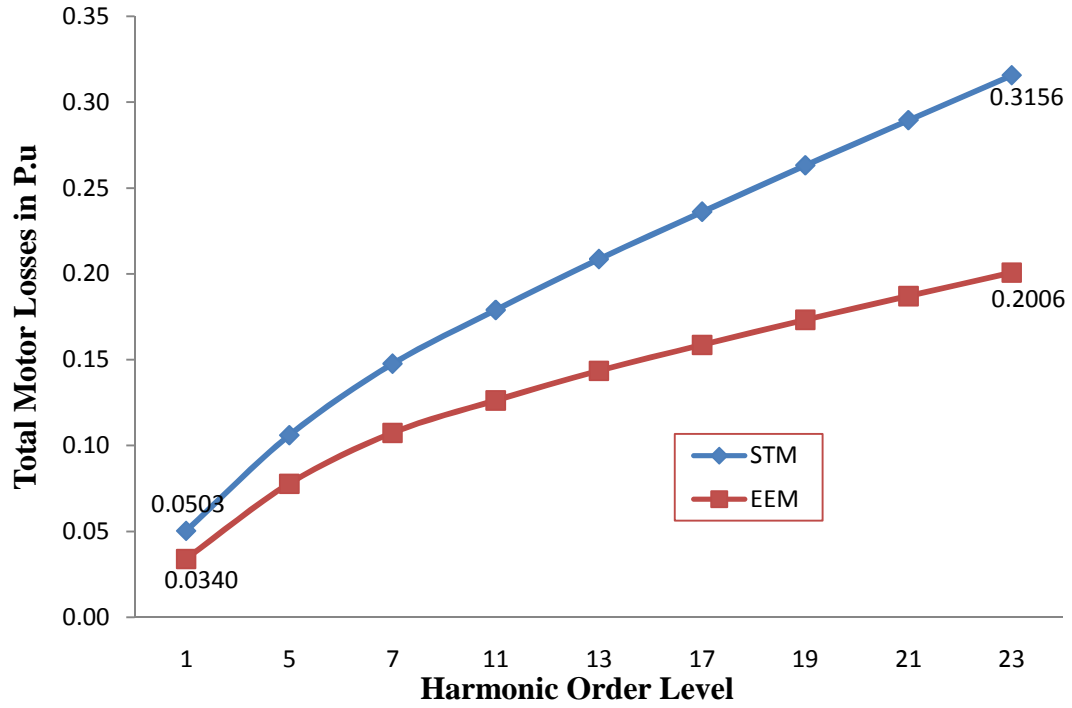


Figure 4.51: Cummulative Total Losses for 250HP Motors

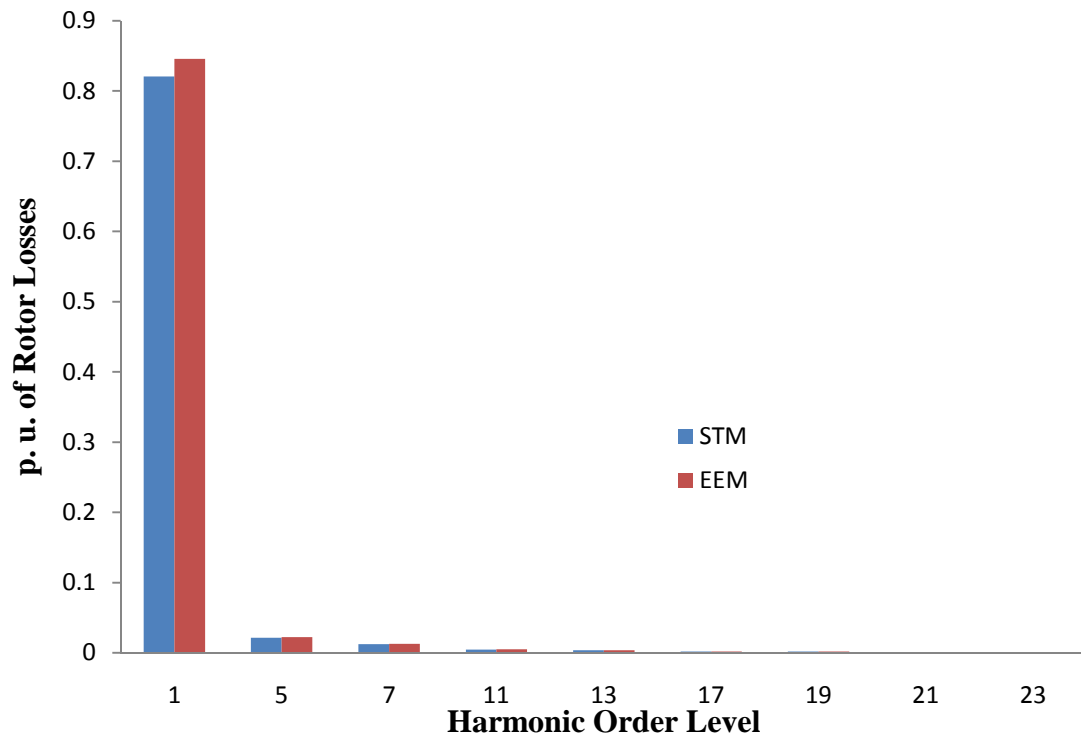


Figure 4.52: Rotor Losses for 250HP Motors vs. Harmonic Order Level

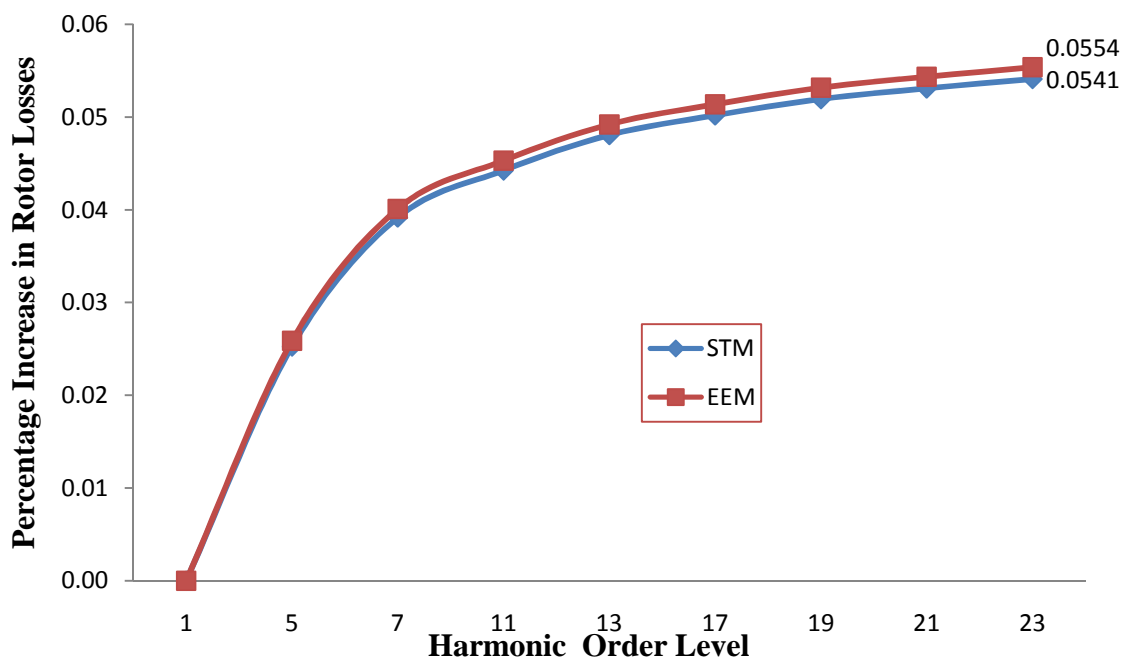


Figure 4.53: Percent Increase in Rotor Losses for 250 HP Motors vs. Harmonic Order Level

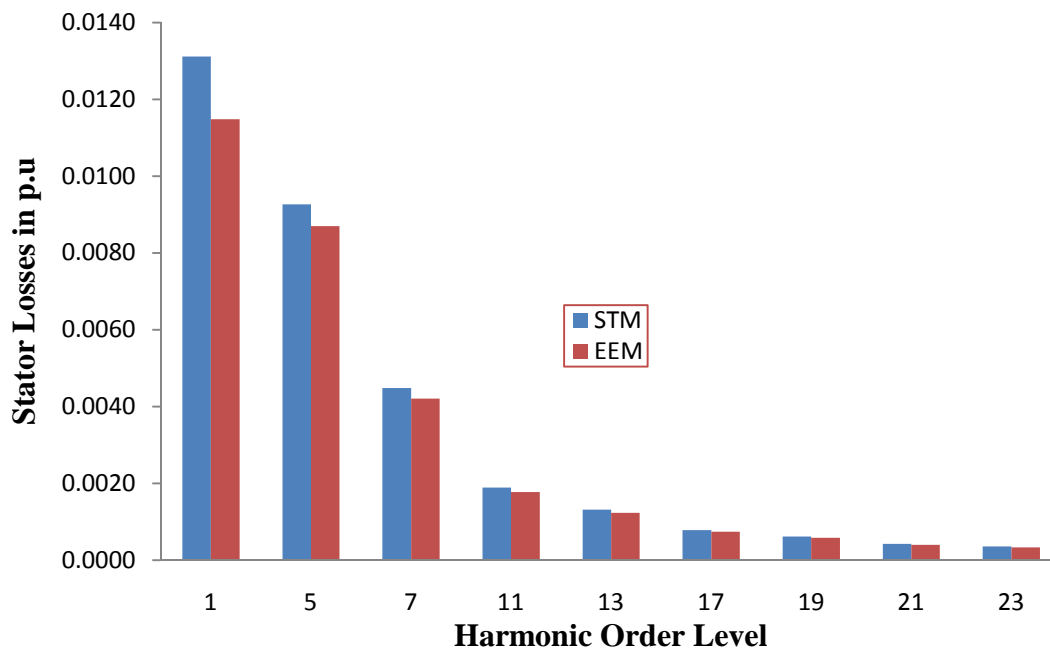


Figure 4.54: Stator Losses for 250 HP Motors vs. Harmonic Order Level

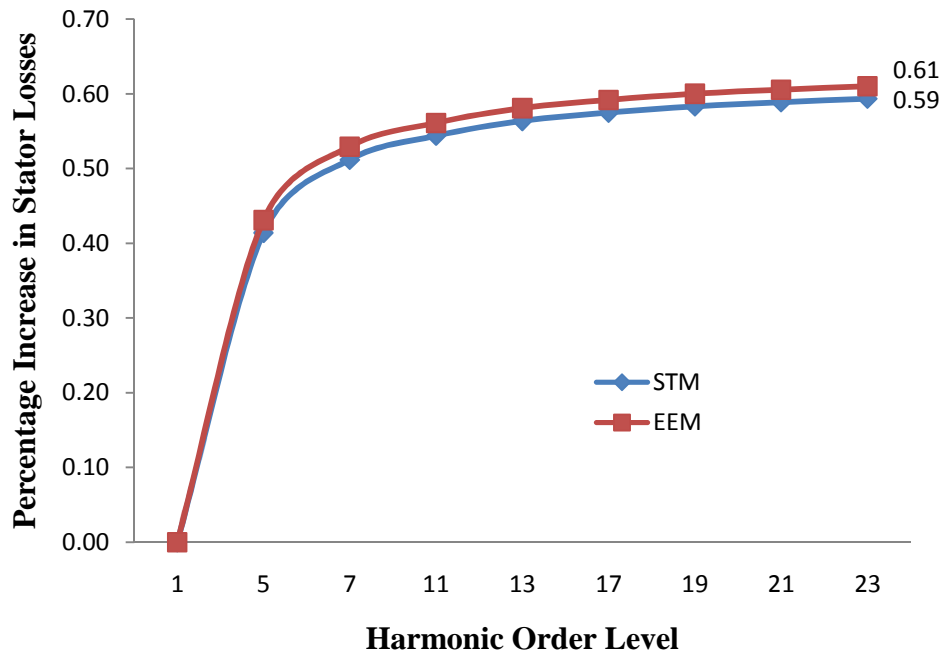


Figure 4.55: Percent Increase in Stator Losses for 250 HP Motors vs. Harmonic Order Level

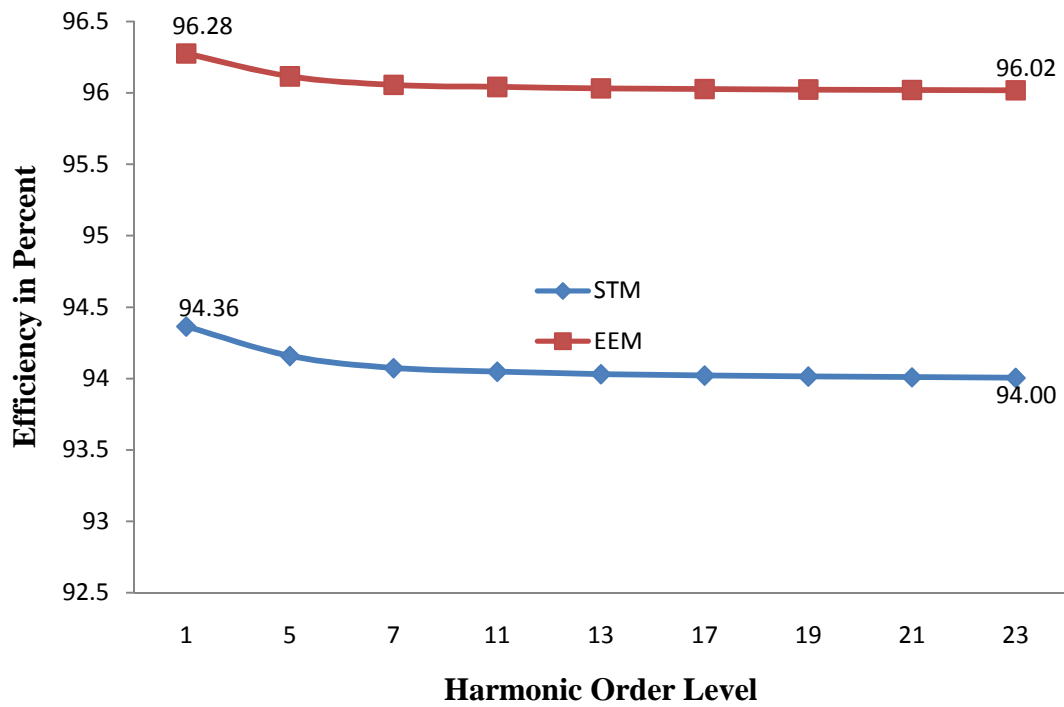


Figure 4.56: Efficiencies for 250 HP Motors vs. Harmonic Order Level

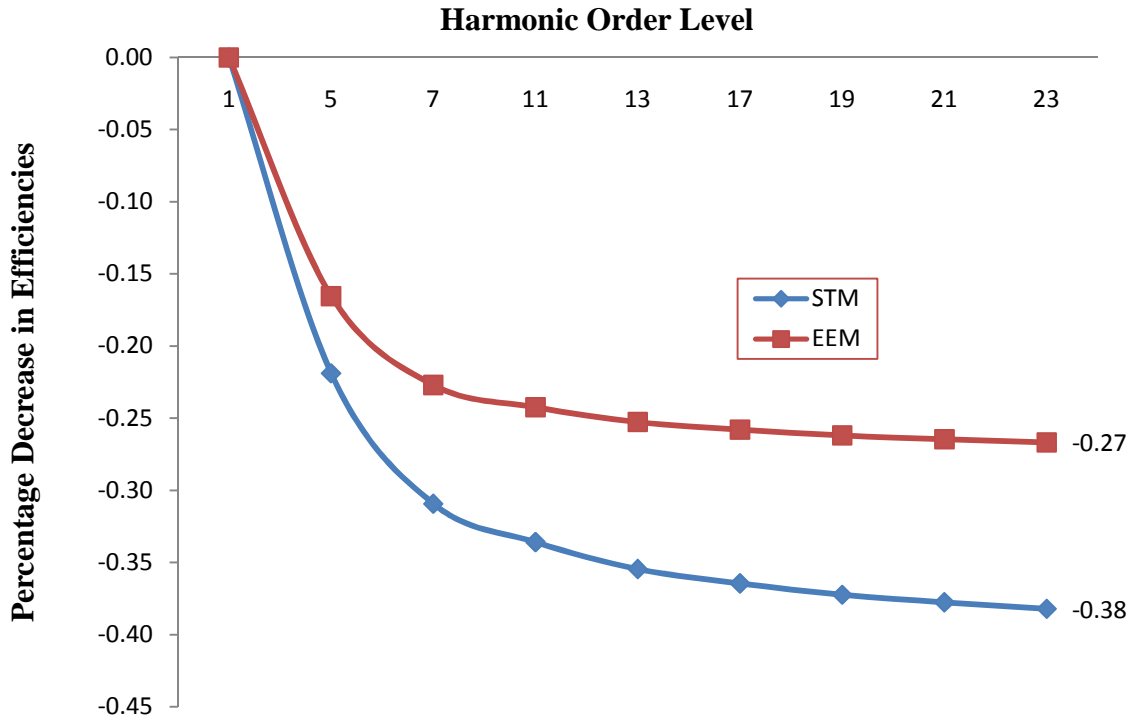


Figure 4.57: Percent Decrease In Efficiencies for 250 HP Motors vs. Harmonic Order Level



Figure 4.58: Yearly Savings for 250 HP EEM over STM vs. Harmonic Order Level

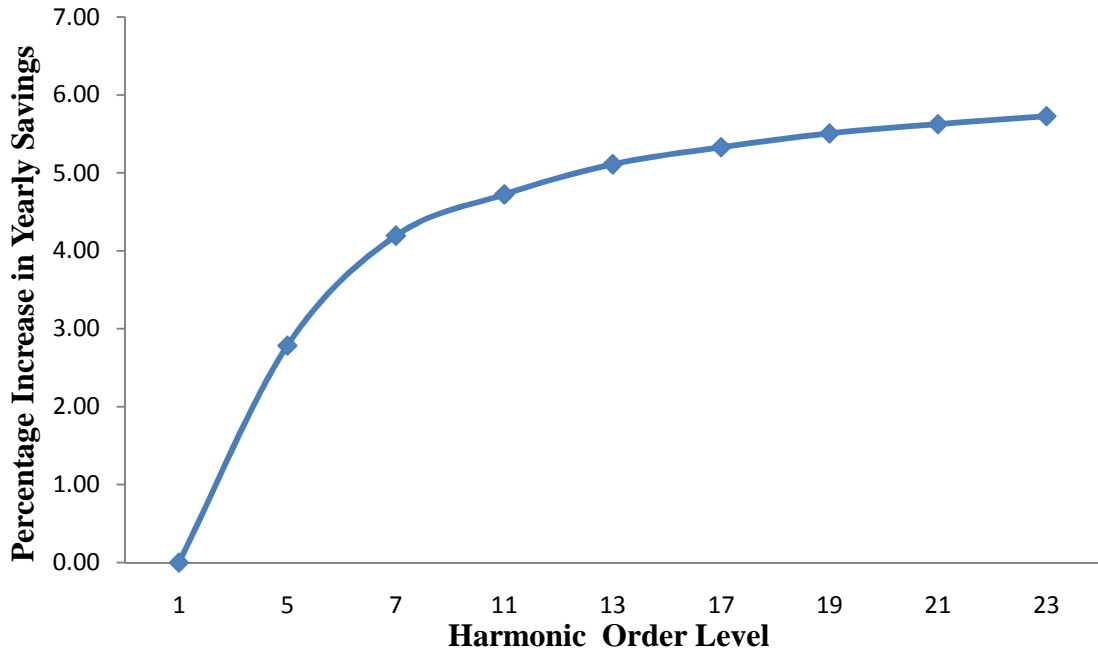


Figure 4.59: Percent Increase in Yearly Savings for 250 HP EEM over STM vs. Harmonic Order Level

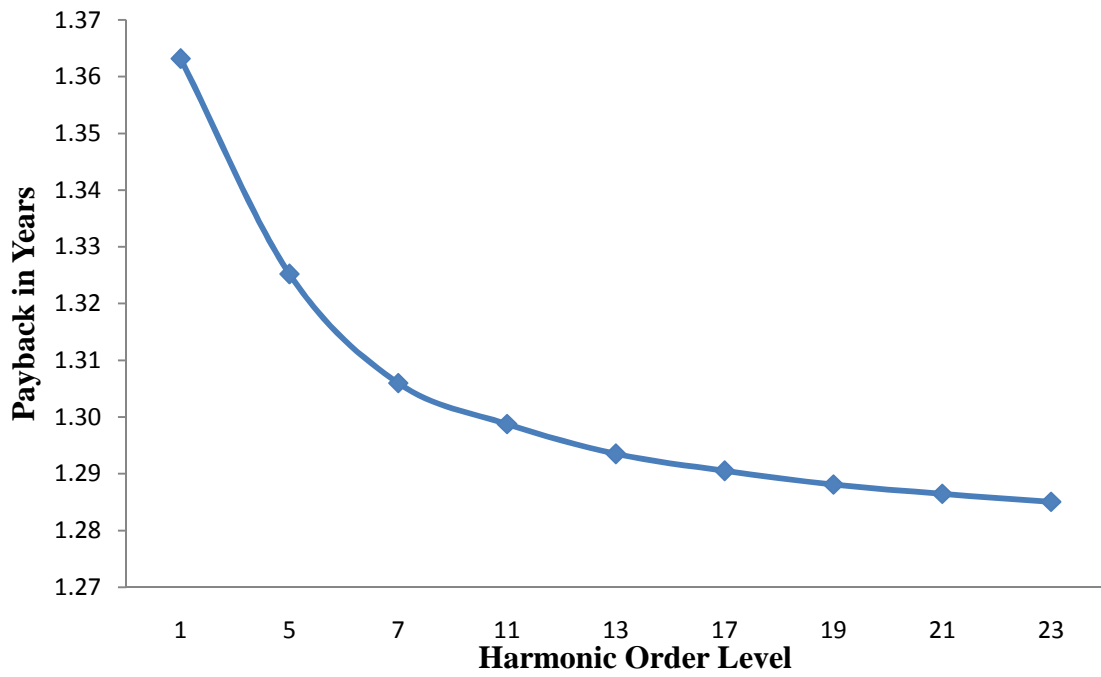


Figure 4.60: Payback Time for 250 HP Motors vs. Harmonic Order Level

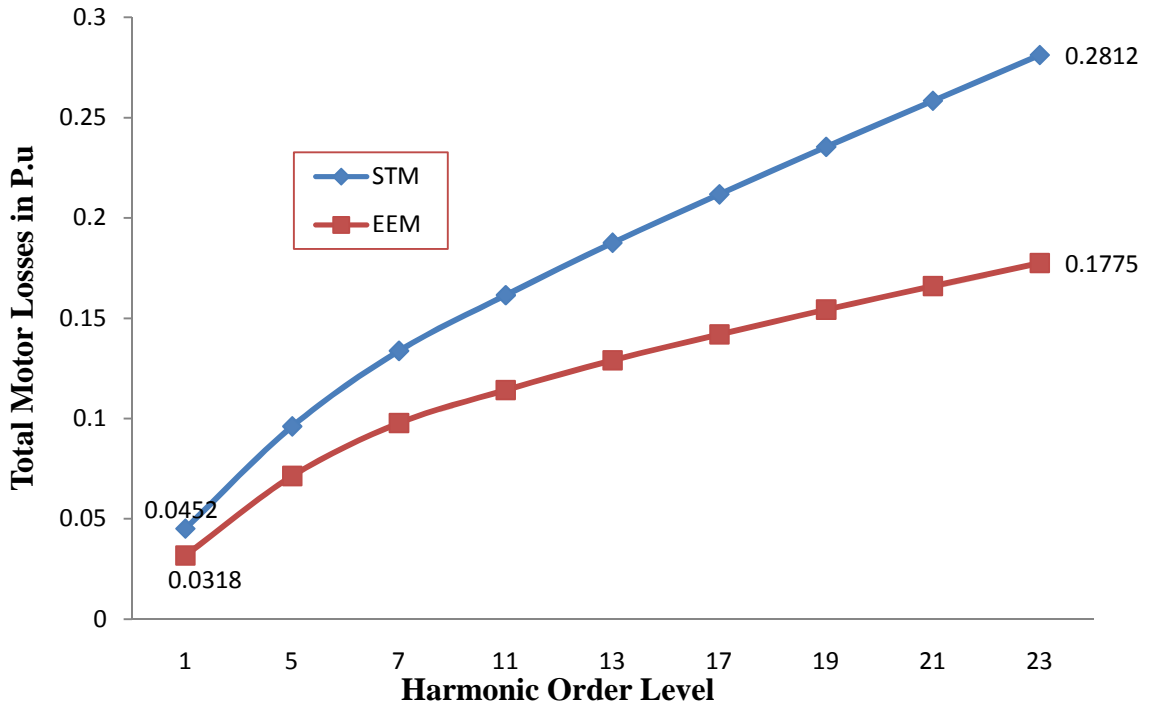


Figure 4.61: Cummulative Total Losses for 300HP Motors

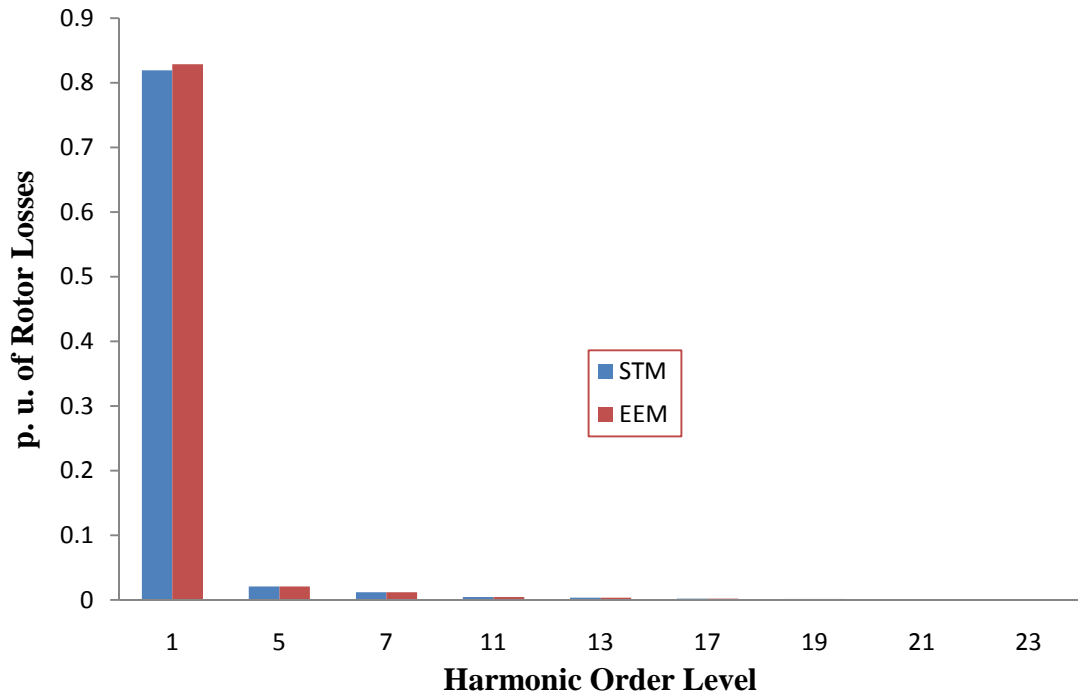


Figure 4.62: Rotor Losses for 300HP Motors vs. Harmonic Order Level

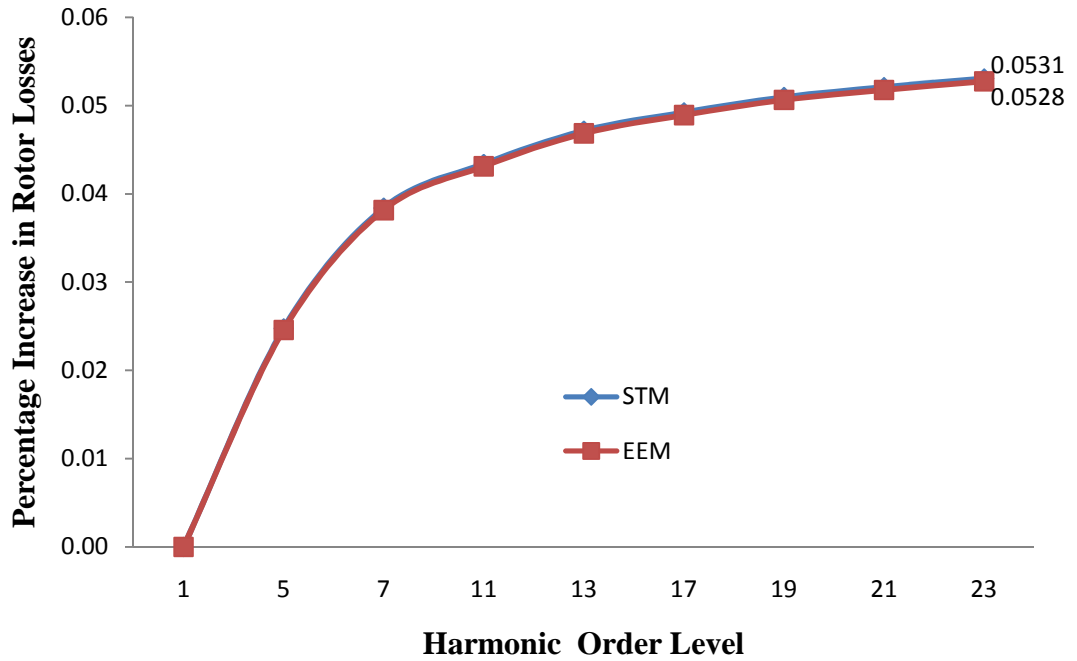


Figure 4.63: Percent Increase in Rotor Losses for 300 HP Motors vs. Harmonic Order Level

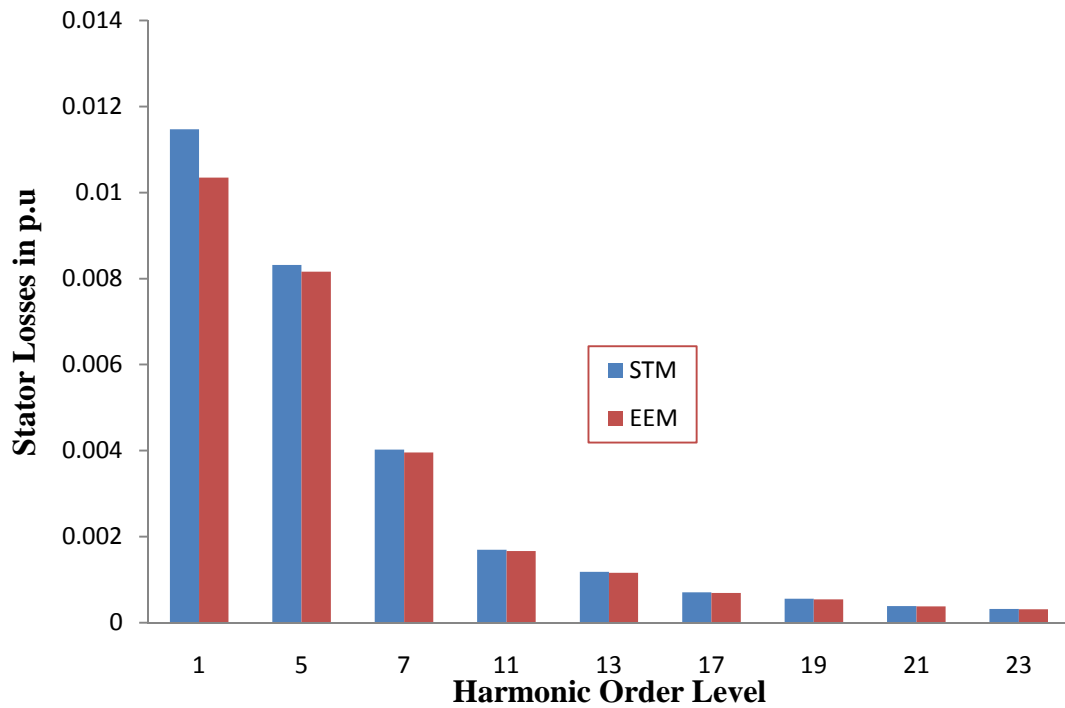


Figure 4.64: Stator Losses for 300 HP Motors vs. Harmonic Order Level

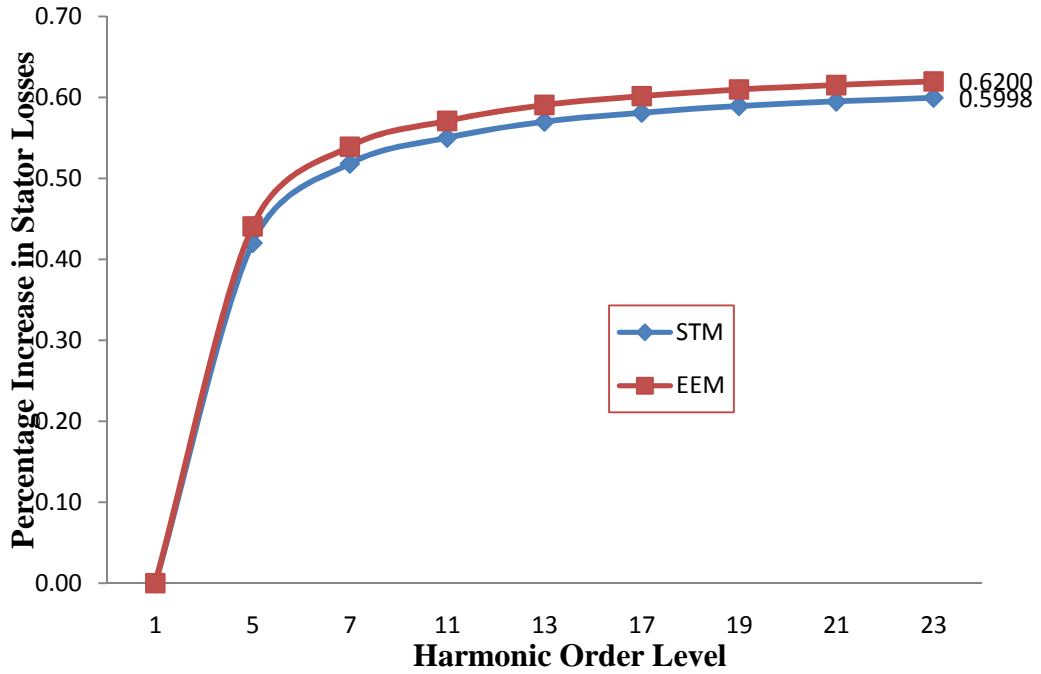


Figure 4.65: Percent Increase in Stator Losses for 300 HP Motors vs. Harmonic Order Level

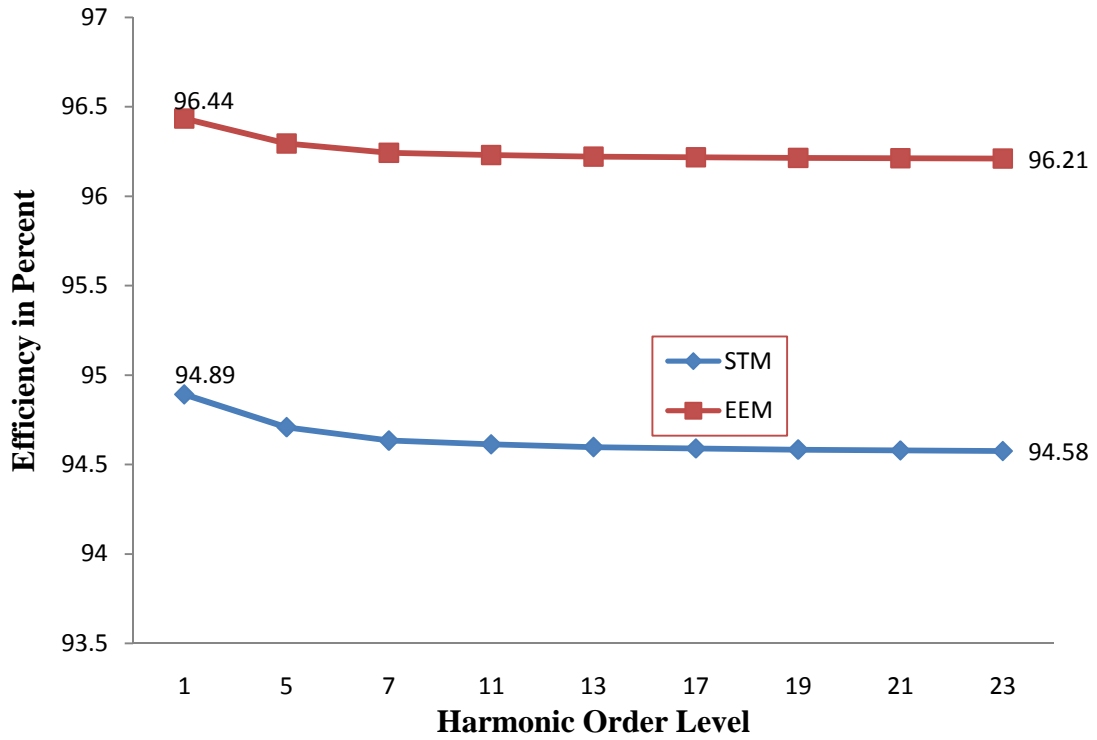


Figure 4.66: Efficiencies for 300 HP Motors vs. Harmonic Order Level

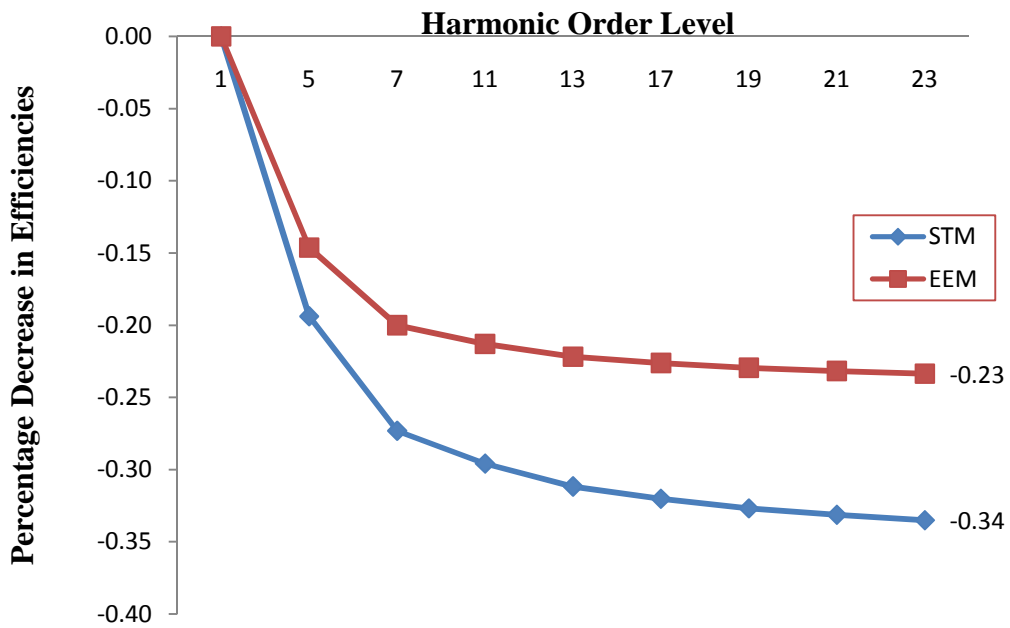


Figure 4.67: Percent Decrease In Efficiencies for 300 HP Motors vs. Harmonic Order Level

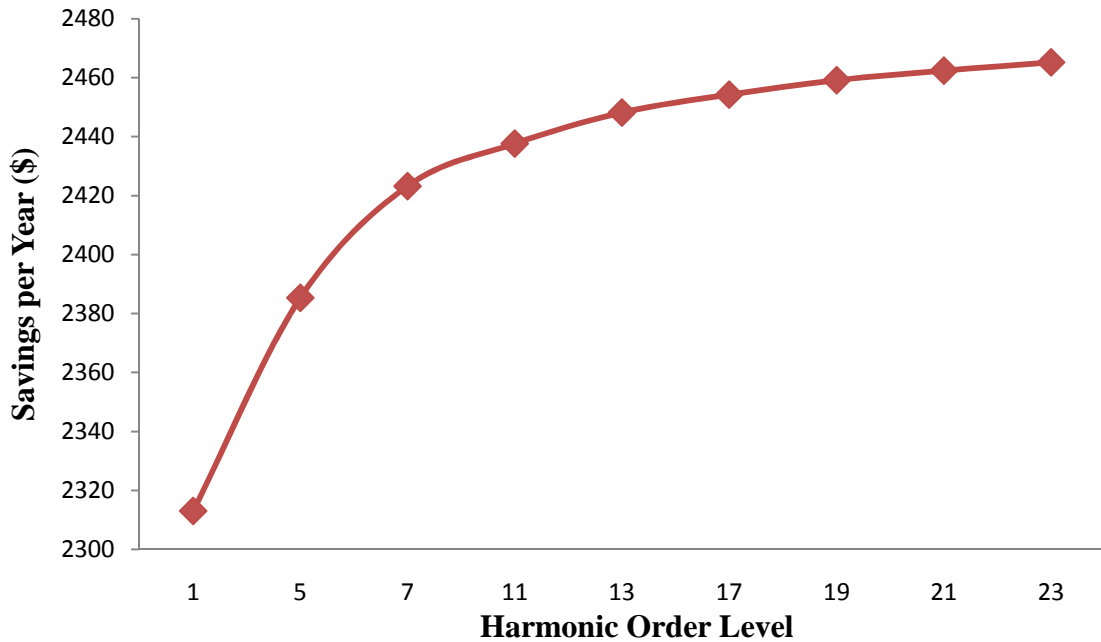


Figure 4.68: Yearly Savings for 300 HP EEM over STM vs. Harmonic Order Level

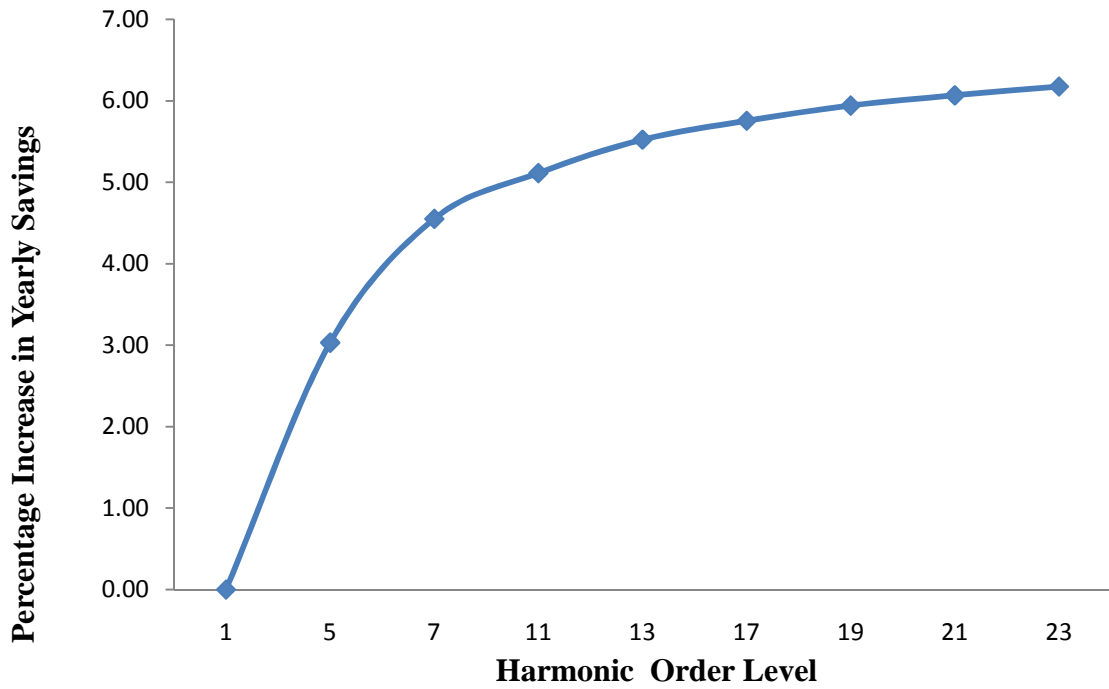


Figure 4.69: Percent Increase in Yearly Savings for 300 HP EEM over STM vs. Harmonic Order Level

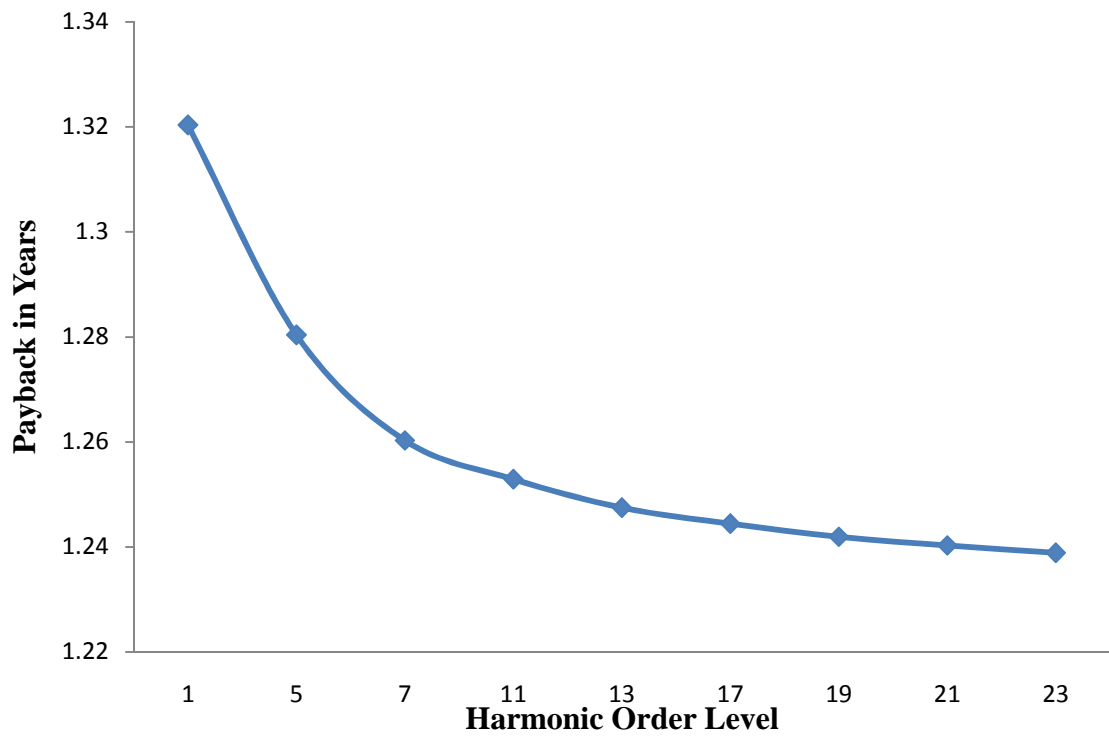


Figure 4.70: Payback Time for 300 HP Motors vs. Harmonic Order Level

CHAPTER 5

CONCLUSION

In this study, the behavior of the energy efficient and the standard motors when subjected to harmonic conditions were investigated and compared. The skin effect impedance model was used in the analysis of this study. Computer program was used to simulate the characteristic of the motors. The losses due to harmonic were calculated and documented; the efficiencies of the motors and its economic impact on these motors were well understood. In addition, the harmonic orders that contributed the most loss to the motors' total losses were identified.

The methodology adopted in this study supported the overall objective of this research. It was determined and verified that energy efficient motor is more cost efficient even under harmonic load. However, the EEM is more susceptible to harmonics than the STM, this is due to the skin effect in the rotor bars of the motor construction. As shown in Figures 5.1 and 5.2, the largest percentage increase in rotor loss for the EEM is 11.43% at 100hp and for the STM is 10.41% at 50hp. In all, the percentage increases in rotor loss of the EEMs are higher than those of the corresponding STMs at higher rating (above 100hp), whereas the STMs have a slightly higher percentage increase in rotor loss for motors greater than 100hp.

It was found that the order of harmonics that contributed mostly to the rotor loss as shown in Figures 5.3 and 5.4 are at the 5th and 7th harmonics. The 5th harmonics is responsible for over 45% of the total rotor loss and the 7th harmonics contributed about

25% of the loss. Clearly, the effects of the 5th and 7th harmonics are highly significant and continuous research need to be ongoing in minimizing the impact of these harmonics.

The percentage drop of efficiencies of both EEM and STM were compared as shown in Figures 5.5 and 5.6 respectively. The figures show a convincing impact the 5th and 7th harmonics have on the total rotor loss. The 5th harmonics is responsible for over 65% of the drop in efficiencies for both EEM and STM whereas the 7th harmonics contributed over 25% to the drop in efficiencies of the motors.

In addition, the drops of efficiencies of the STM and EEM at 5th and 7th harmonics were compared as shown in Figures 5.7 and 5.8. Figure 5.7 shows a higher drop in efficiencies for the EEM at the 5th harmonics but slightly lower drop in efficiencies in the 7th harmonics.

The economic evaluation methodology was adapted to include the impact of harmonics. At each order of harmonic, the simple payback method was used to calculate the payback period. Figure 5.9 show the trend of payback period for each EEMs and STMs. The highest annual savings achieved from the simple payback analysis is \$2520 for the 250hp motors while the shortest payback period is 1.26years for the 300hp motors. The longest payback period is 4.6years for the 25hp motors.

In conclusion, the overall objective of this study was achieved. The results of this research buttress the under-study impact of harmonics on Energy Efficient. As more and more standard motors are being replaced with energy efficient motors, these motors are being designed to optimize the skin effect phenomena which when subjected to harmonics load, the rotor speed reduced and rotor bar resistance increases thereby decreasing the motor efficiencies.

Further research is expected to look into how to further minimize losses due to non sinusoidal load on EEM. Additional more research should be conducted on the impact of the 5th and 7th harmonics on energy efficient motors.

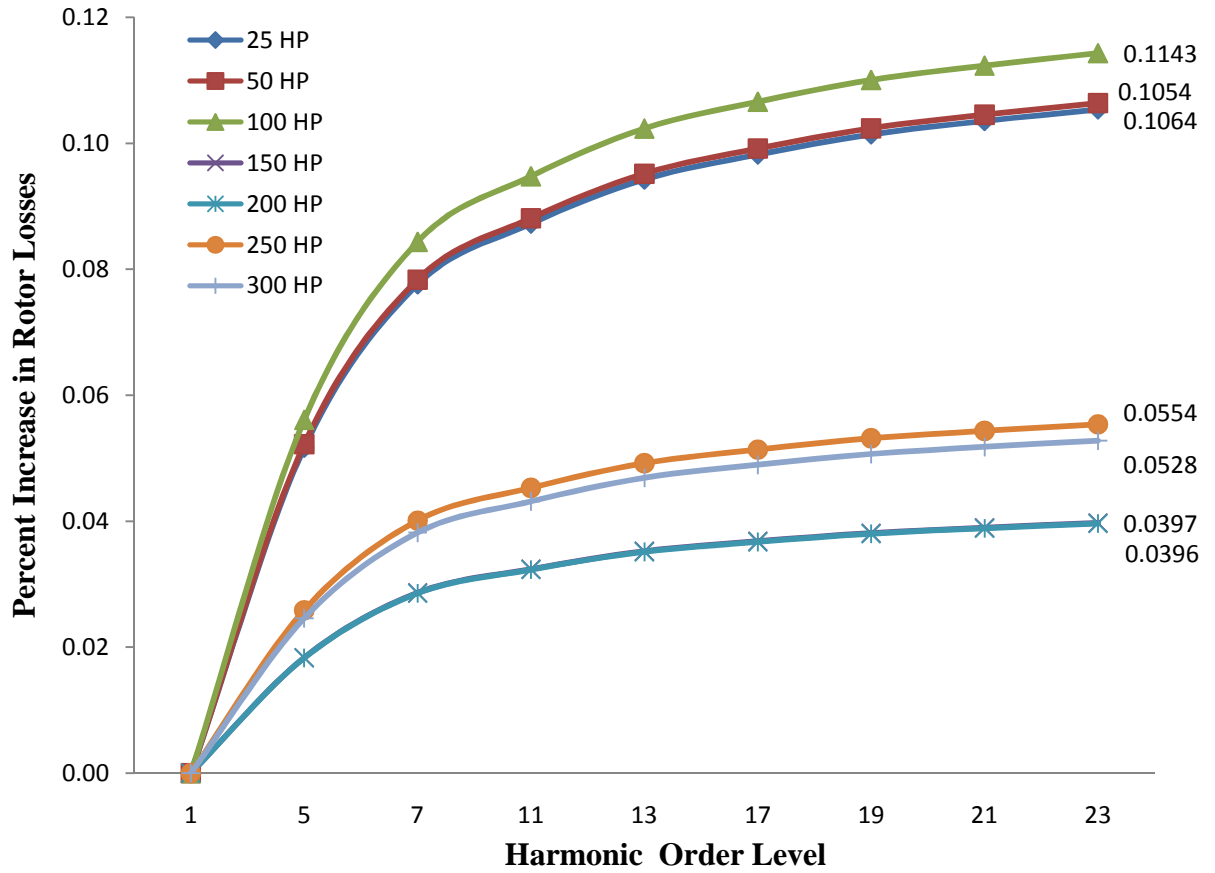


Figure 5.1: EEMs Rotor Losses Vs. Harmonic Order Level

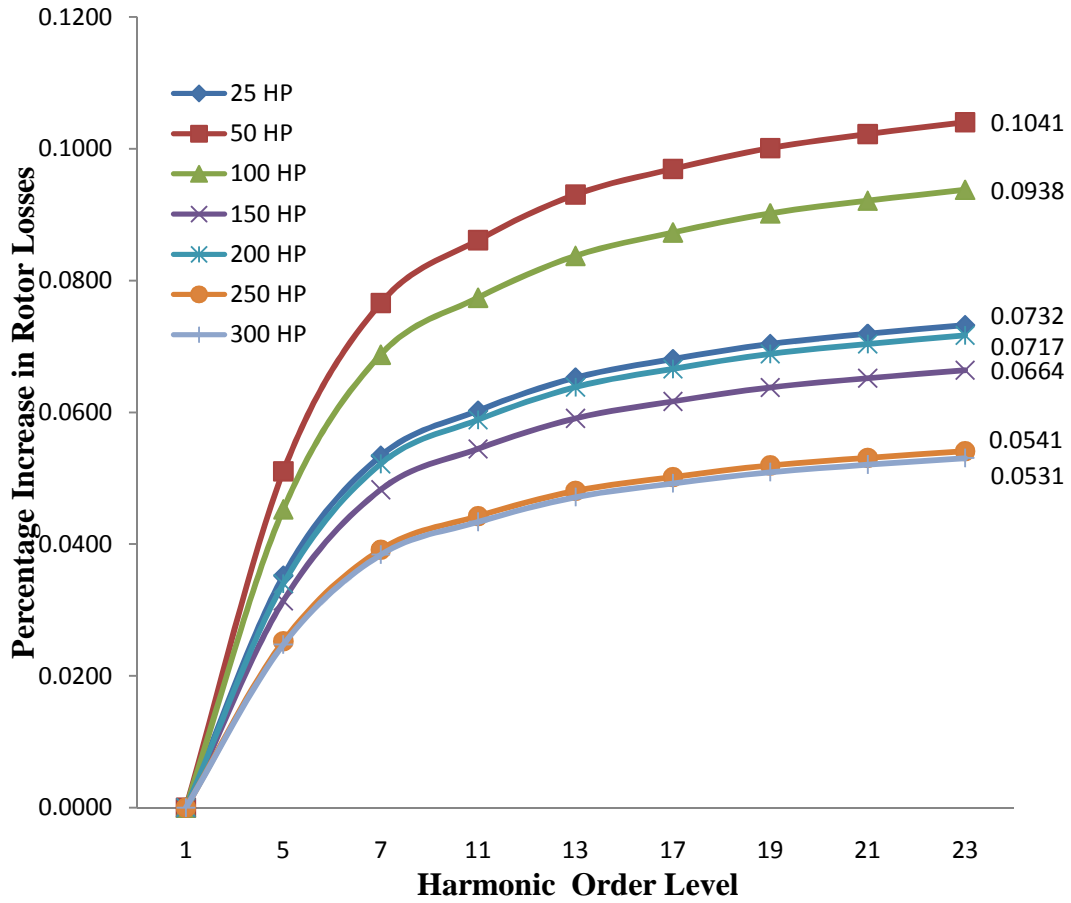


Figure 5.2: STMs Rotor Losses Vs. Harmonic Order Level

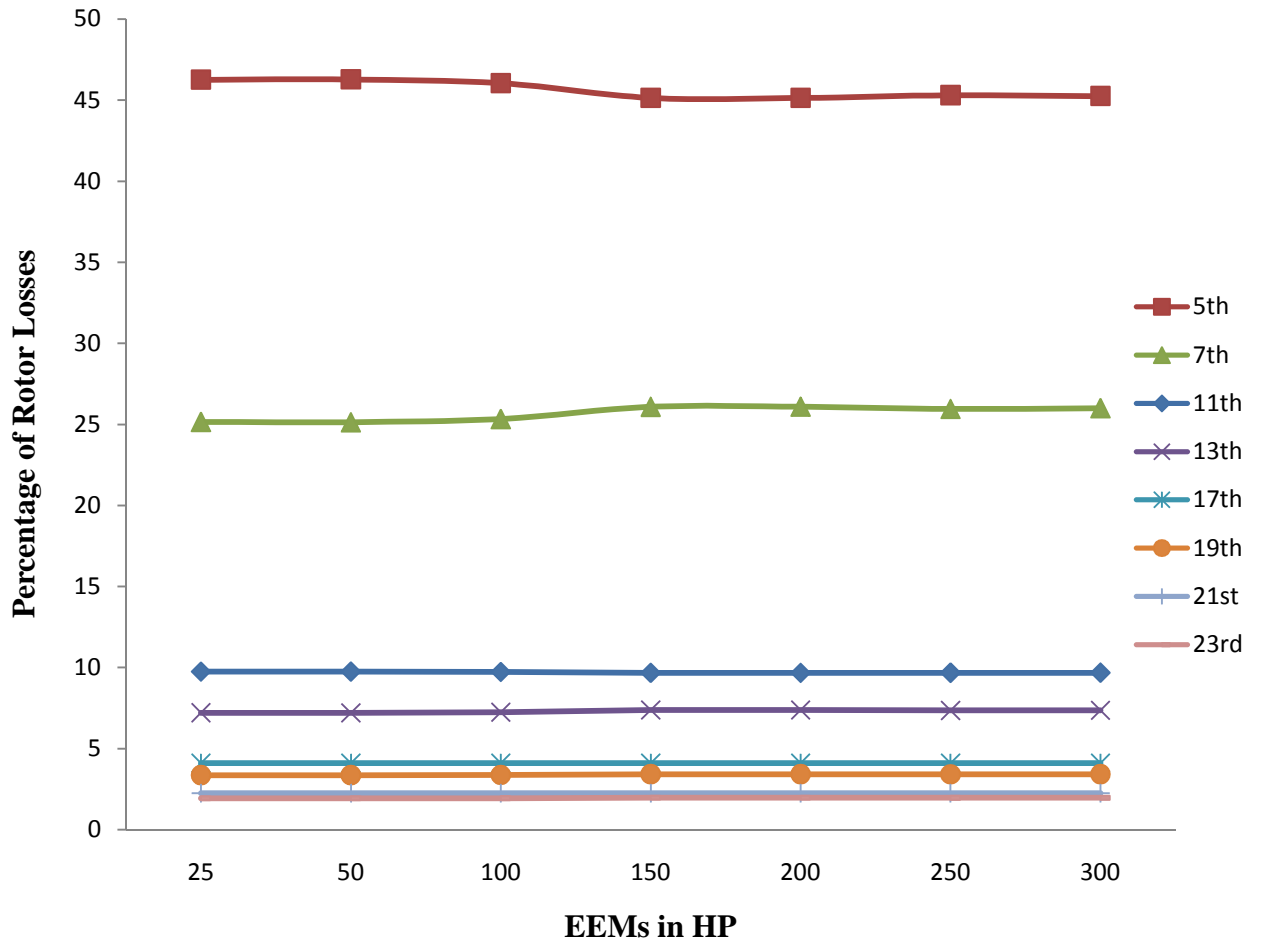


Figure 5.3: Percentage of Rotor Loss due to Each Harmonics Vs. EEMs

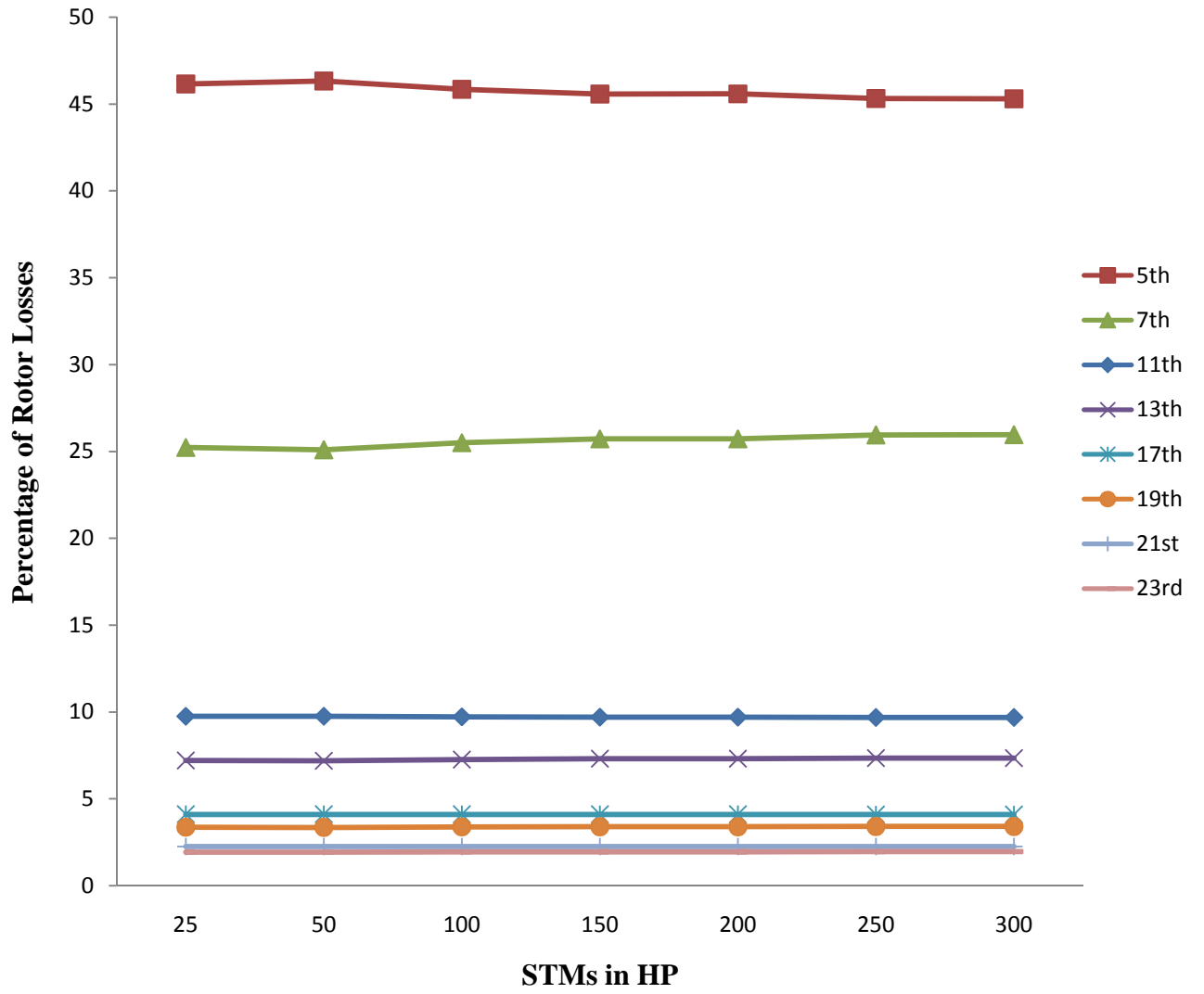


Figure 5.4: Percentage of Rotor Loss due to Each Harmonics Vs. STMs

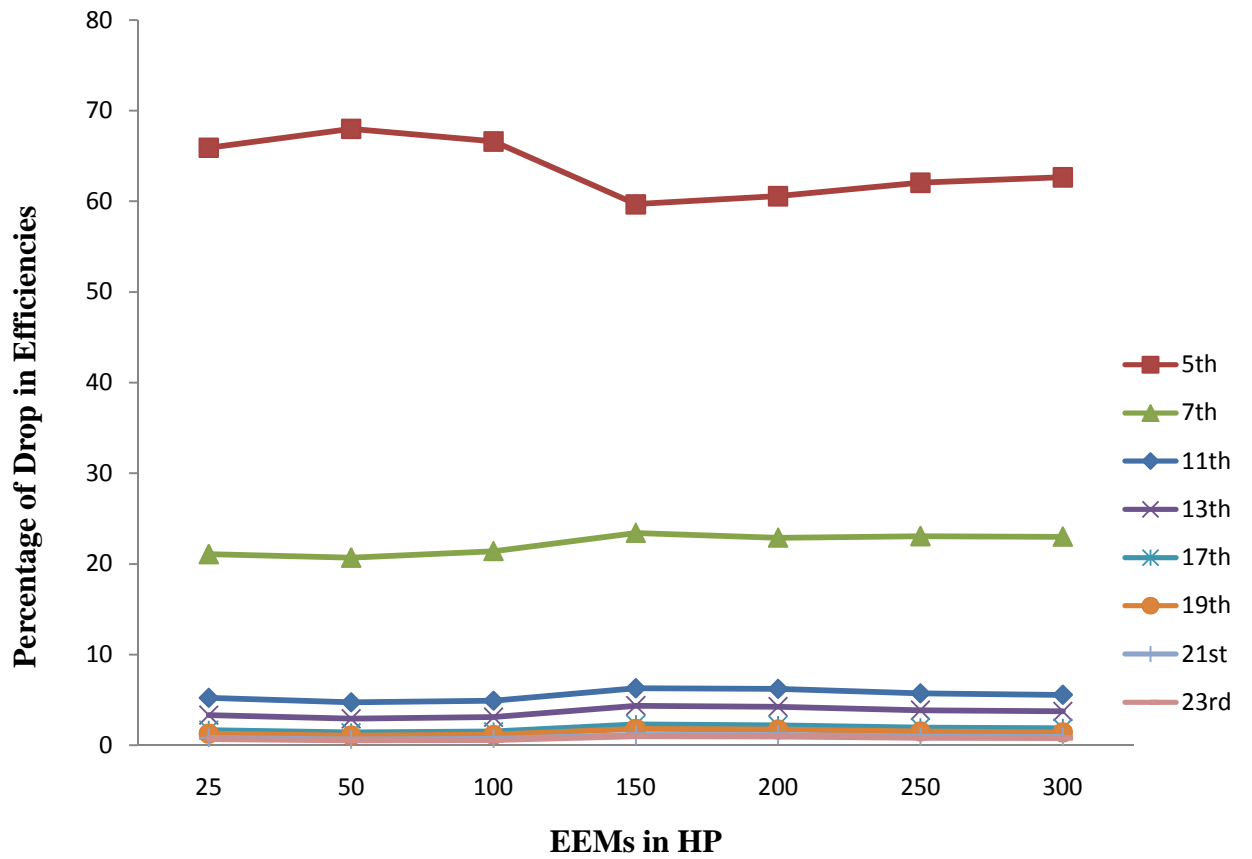


Figure 5.5: Rate of Drop in Efficiencies due to Each Harmonics Vs. EEMs

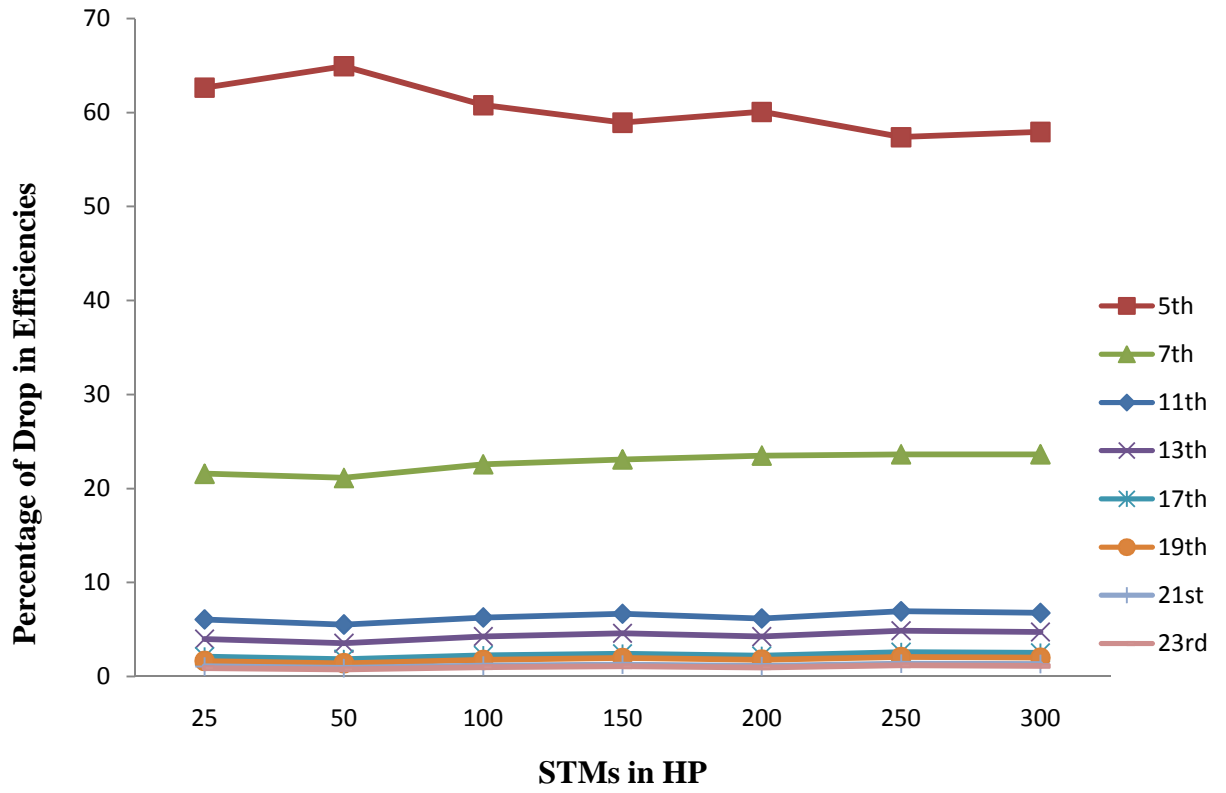


Figure 5.6: Rate of Drop in Efficiencies due to Each Harmonics Vs. STMs

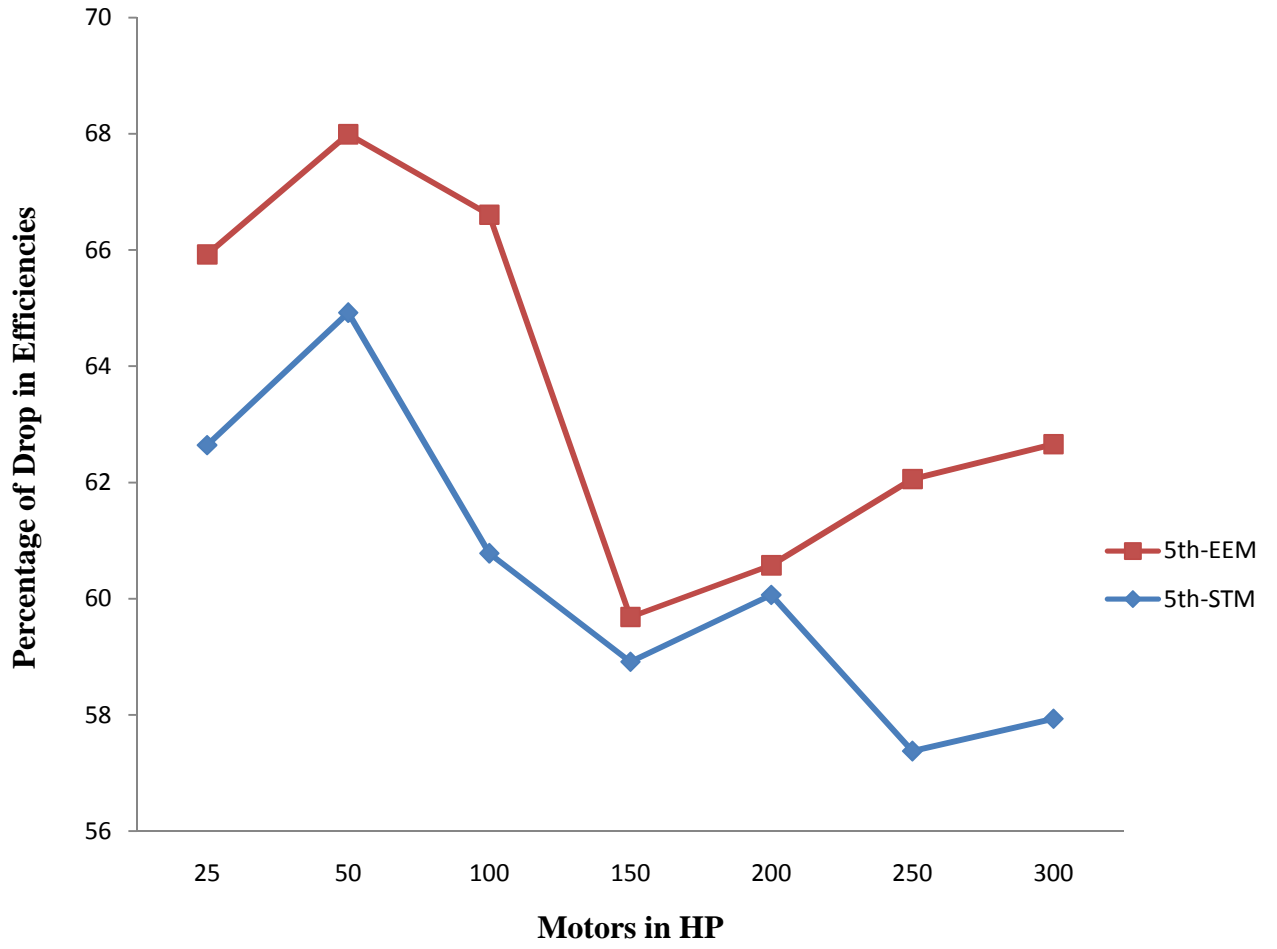


Figure 5.7: Rate of Drop in Efficiencies for EEMs and STMs @ 5th Harmonics

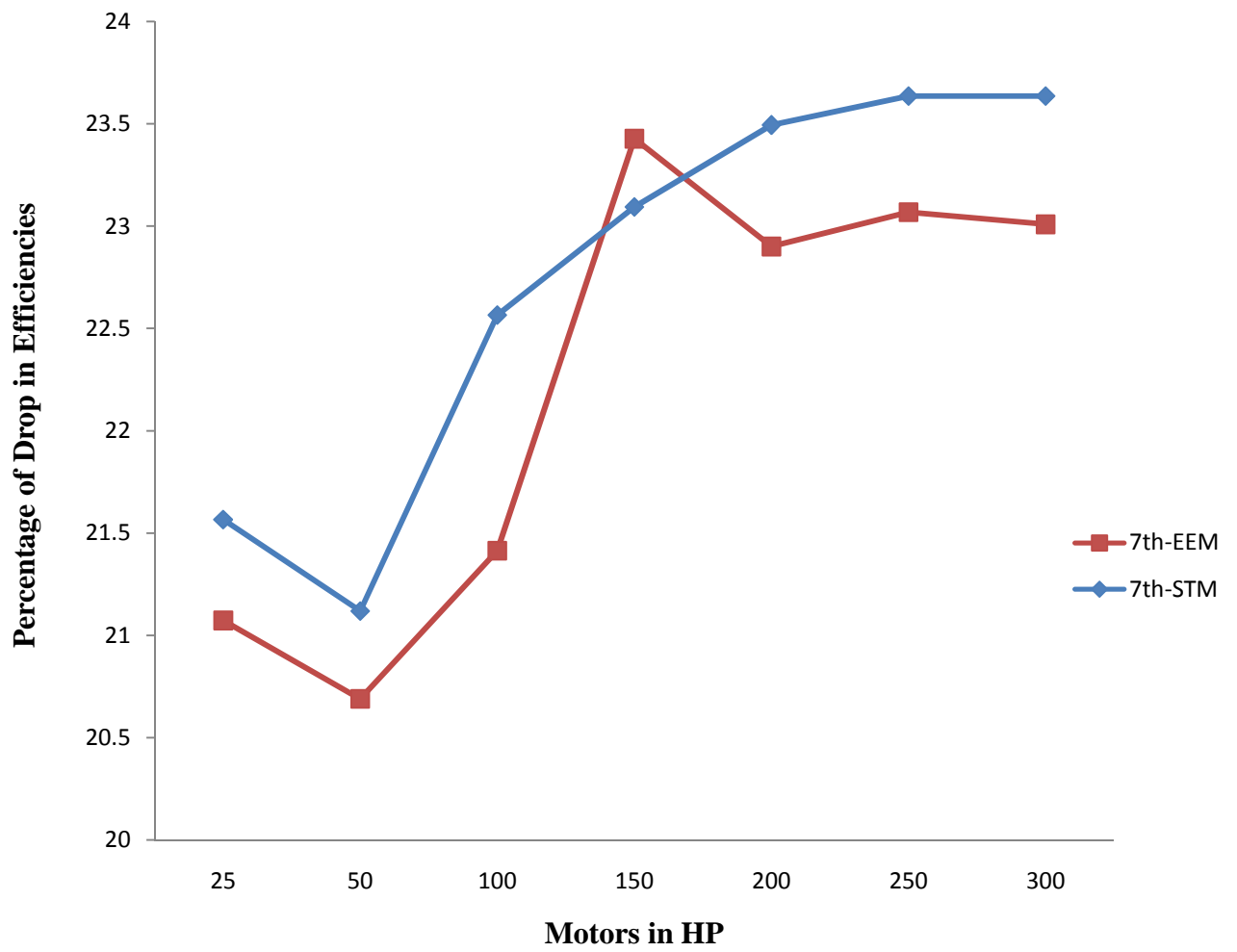


Figure 5.8: Percentage of Drop in Efficiencies for EEMs and STMs @ 7th Harmonics

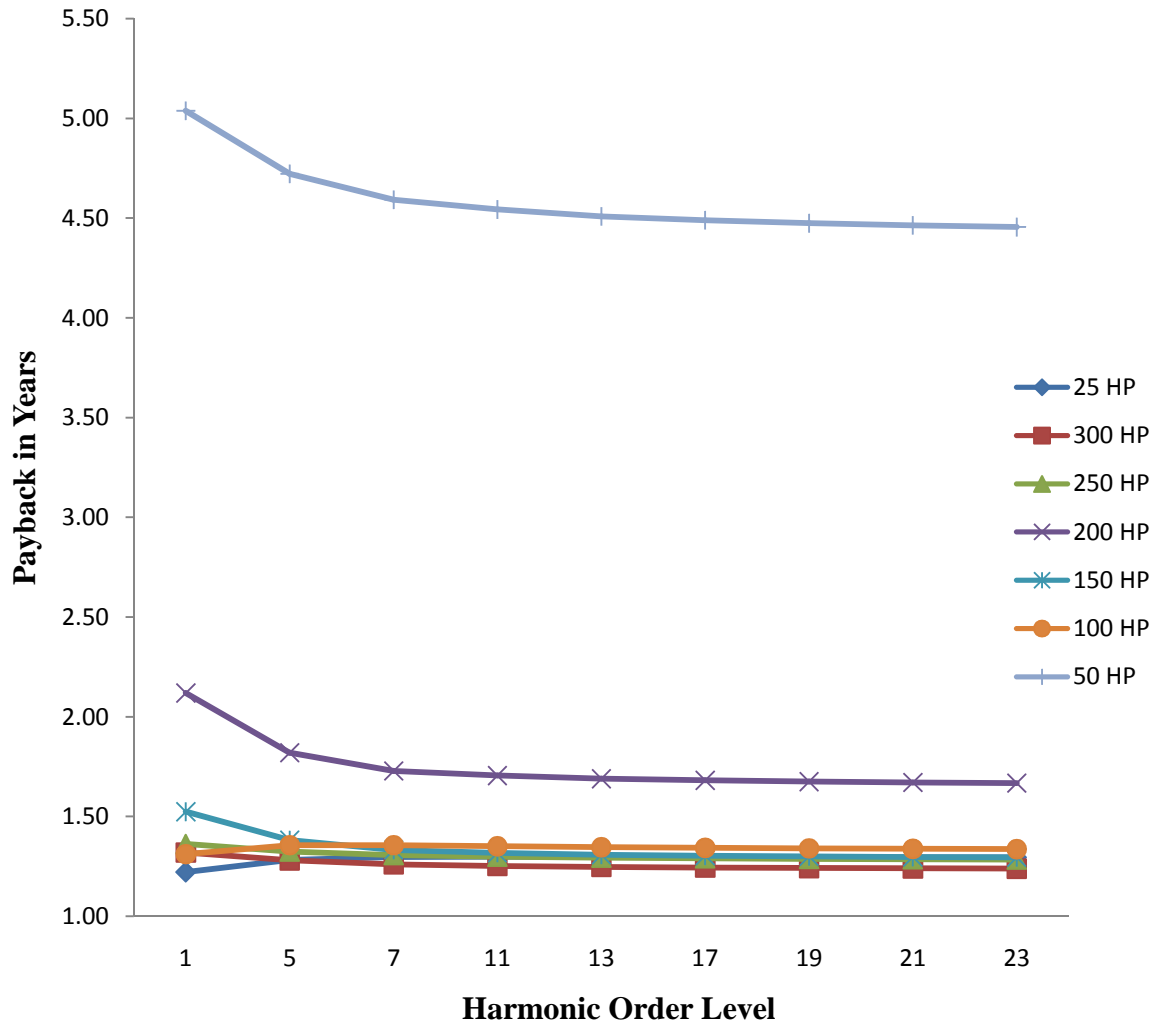


Figure 5.9: Percentage of Drop in Efficiencies for EEMs and STMs @ 7th Harmonics

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APPENDICES

APPENDIX A

Computer Program

```
%COMPUTER PROGRAM
%THESIS TITLE: EFFECT OF HARMONIC ON THE EFFICIENCY OF A THREE
%PHASE ENERGY EFFICIENT MOTORS
%AUTHOR: OLADOKUN E. FADUYILE
%ADVISOR: DR AHMED ELTOM
%DATE: JUNE, 2009
clc
clear
PinStd_FL=0;
PoutStd_FL=0;
effStd_FL=0;
PinEff_FL=0;
PoutEff_FL=0;
effEff_FL=0;

%Input Data for 300HP
%horsePower=300; EEMCost = 14009.57; STMCost = 10955.54;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.0255; XsEff=0.3064; XmEff=11.55; XrEff=0.3591; RrEff=0.0197; RrstEff=0.0632;
%RsStd=0.0274; XsStd=0.3334; XmStd=10.83; XrStd=0.3466; RrStd=0.0204; RrstStd=0.0662;
%PStd_NL_Loss = 5724; PStd_FL_Loss = 12014;
%PEff_NL_Loss = 2658; PEff_FL_Loss = 8232;
%VLLEff_FL=796.74; VLLStd_FL=796.74; EffMotorStd=94.9; EffMotorEff = 96.5;
%StdMotorRPM=1784; EffMotorRPM=1785; powFactorStd=88.7; powFactorEff=89.5;

%Input Data for 250HP
%horsePower=250; EEMCost = 13020.27; STMCost = 9740.18;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.0312; XsEff=0.3862; XmEff=12.65; XrEff=0.4181; RrEff=0.0221; RrstEff=0.0769;
%RsStd=0.0355; XsStd=0.4120; XmStd=11.73; XrStd=0.4016; RrStd=0.0227; RrstStd=0.0780;
%PStd_NL_Loss = 5589; PStd_FL_Loss = 11337;
%PEff_NL_Loss = 2691; PEff_FL_Loss = 7441;
%VLLEff_FL=796.74; VLLStd_FL=796.74; EffMotorStd=94.3; EffMotorEff = 96.2;
%StdMotorRPM=1785; EffMotorRPM=1786; powFactorStd=87.8; powFactorEff=88.6;

%Input Data for 200HP
%horsePower=200; EEMCost = 10378.57; STMCost = 7413.92;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.0392; XsEff=0.4123; XmEff=13.69; XrEff=0.6688; RrEff=0.0329; RrstEff=0.0939;
%RsStd=0.0489; XsStd=0.4264; XmStd=15.19; XrStd=0.5376; RrStd=0.0353; RrstStd=0.1137;
%PStd_NL_Loss = 3769; PStd_FL_Loss = 8512; PEff_NL_Loss = 1967; PEff_FL_Loss = 6299;
%VLLEff_FL=796.74; VLLStd_FL=796.74; EffMotorStd=94.6; EffMotorEff = 95.9;
%StdMotorRPM=1782; EffMotorRPM=1783; powFactorStd=88.8; powFactorEff=86.3;
```



```

%Input Data for 150HP
%horsePower=150; EEMCost = 8532.74; STMCost = 6102.37;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.0571; XsEff=0.5505; XmEff=16.43; XrEff=0.8582; RrEff=0.0435; RrstEff=0.1216;
%RsStd=0.0742; XsStd=0.6296; XmStd=19.15; XrStd=0.7053; RrStd=0.0506; RrstStd=0.1581;
%PStd_NL_Loss = 3480; PStd_FL_Loss = 7580; PEff_NL_Loss = 1659; PEff_FL_Loss = 5030;
%VLLEff_FL=796.74; VLLStd_FL=796.74; EffMotorStd=93.7; EffMotorEff = 95.7;
%StdMotorRPM=1780; EffMotorRPM=1783; powFactorStd=87.8; powFactorEff=85.4;
%Input Data for 100HP
%horsePower=100; EEMCost = 5575.41; STMCost = 3889.40;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.0970; XsEff=0.7979; XmEff=23.72; XrEff=0.9829; RrEff=0.0618; RrstEff=0.2352;
%RsStd=0.1009; XsStd=0.8523; XmStd=23.12; XrStd=1.0107; RrStd=0.0640; RrstStd=0.2332;
%PStd_NL_Loss = 2549; PStd_FL_Loss = 5644; PEff_NL_Loss = 1278; PEff_FL_Loss = 3610;
%VLLEff_FL=796.74; VLLStd_FL=796.74; EffMotorStd=93; EffMotorEff = 95.4;
%StdMotorRPM=1783; EffMotorRPM=1784; powFactorStd=86.2; powFactorEff=87.0;

%Input Data for 50HP
%horsePower=50; EEMCost = 3889.40; STMCost = 1680.50;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.3378; XsEff=1.5512; XmEff=57.55; XrEff=2.3542; RrEff=0.1945; RrstEff=0.6282;
%RsStd=0.0314; XsStd=0.1338; XmStd=5.08; XrStd=0.2001; RrStd=0.0162; RrstStd=0.0537;
%PStd_NL_Loss = 1006; PStd_FL_Loss = 3084; PEff_NL_Loss = 554; PEff_FL_Loss = 2350;
%VLLEff_FL=796.74; VLLStd_FL=230; EffMotorStd=92.4; EffMotorEff = 94.1;
%StdMotorRPM=1774; EffMotorRPM=1775; powFactorStd=85.6; powFactorEff=88.3;

%Input Data for 25HP
%horsePower=25; EEMCost = 1308.31; STMCost = 887.35;
%percentOper = 1; elecCost = 0.07; runTime = 8760;
%RsEff=0.2239; XsEff=1.0215; XmEff=31.20; XrEff=1.6269; RrEff=0.1266; RrstEff=0.4169;
%RsStd=0.9444; XsStd=2.9329; XmStd=112.28; XrStd=4.1341; RrStd=0.5215; RrstStd=1.1763;
%PStd_NL_Loss = 561; PStd_FL_Loss = 1903; PEff_NL_Loss = 393; PEff_FL_Loss = 1325;
%VLLEff_FL=460; EffMotorEff = 93.4; EffMotorRPM=1775; powFactorEff=85.9;
%VLLStd_FL=796.74; EffMotorStd=90.7; StdMotorRPM=1765; powFactorStd=89.4;

%Converting Data to Per Unit
powerIn=(horsePower*746)/(EffMotorEff/100);
pBase=(powerIn/(powFactorEff/100));
powerInpu=powerIn/pBase;
zBase=VLLEff_FL^2/pBase;
VsEff_FL=VLLEff_FL/sqrt(3);
Ibase=VsEff_FL/zBase;
RsEff_FL=RsEff/zBase;
RrEff_FL=RrEff/zBase;
XsEff_FL=XsEff/zBase;
XrEff_FL=XrEff/zBase;
RrEff_LR=RrstEff/zBase;
XmEff_FL=XmEff/zBase;

powerInStd=(horsePower*746)/(EffMotorStd/100);
pBaseStd=(powerInStd/(powFactorStd/100));
powerInpuStd=powerInStd/pBaseStd;

```

```

zBaseStd=VLLStd_FL^2/pBaseStd;
VsStd_FL=VLLStd_FL/sqrt(3);
Ibase=VsStd_FL/zBaseStd;
RsStd_FL=RsStd/zBaseStd;
RrStd_FL=RrStd/zBaseStd;
XsStd_FL=XsStd/zBaseStd;
XrStd_FL=XrStd/zBaseStd;
RrStd_LR=RrStd/zBaseStd;
XmStd_FL=XmStd/zBaseStd;

f=60;
Neff=EffMotorRPM;
Nstd=StdMotorRPM;
p = 4;
Ns=120*f/p;
Sstd_FL=(Ns-Nstd)/Ns;
Seff_FL=(Ns-Neff)/Ns;

slipArrayEff = [Seff_FL,((6-Seff_FL)/5),((6+Seff_FL)/7),((12-Seff_FL)/11),((12+Seff_FL)/13),((18-
Seff_FL)/17),((18+Seff_FL)/19),((24-Seff_FL)/23),((24+Seff_FL)/25)];
slipArrayStd = [Sstd_FL,((6-Sstd_FL)/5),((6+Sstd_FL)/7),((12-Sstd_FL)/11),((12+Sstd_FL)/13),((18-
Sstd_FL)/17),((18+Sstd_FL)/19),((24-Sstd_FL)/23),((24+Sstd_FL)/25)];
harmonicOrder = [1, 5, 7, 11, 13, 17, 19, 23, 25];

for k = 1:length(harmonicOrder);
    harmonicEff(k)=1/harmonicOrder(k);
    powHarmonic(k)=1/harmonicOrder(k);
    Seff_F(k) = slipArrayEff(k);

    % Calculate Skin Effect model values
    % Rotor Resistances
    R1Eff(k)=RrEff_FL/((0.1)*Seff_F(k));
    R2Eff(k)=RrEff_FL/((0.2)*Seff_F(k));
    R3Eff(k)=RrEff_FL/((0.3)*Seff_F(k));
    R4Eff(k)=RrEff_FL/((0.4)*Seff_F(k));

    % Calculate Skin effect model values
    RrEff_NEG_FL=(RrEff_LR-RrEff_FL)*(2-Seff_FL)+RrEff_FL;

    % Internal Inductance of Rotor bar LiiEff
    LiiEff=(RrEff_NEG_FL)^2/RrEff_FL;

    % External Inductance (Gap) of Rotor bar Xg
    XGEff = XrEff_FL-LiiEff/3;

    % Rotor Inductances
    L1Eff=LiiEff*0.1;
    L2Eff=LiiEff*0.2;
    L3Eff=LiiEff*0.3;
    L4Eff=LiiEff*0.4;

```

```

X1Eff=XGEff+L1Eff/2;
X2Eff=L1Eff/2+L2Eff/2;
X3Eff=L2Eff/2+L3Eff/2;
X4Eff=L3Eff/2+L4Eff/2;

%Equivalent Circuit Calculation for Fundamental
Z4_FL(k)=(R3Eff(k)*(R4Eff(k)+j*X4Eff))/(R3Eff(k)+R4Eff(k)+j*X4Eff);
Z3_FL(k)=(R2Eff(k)*(Z4_FL(k)+j*X3Eff)/(R2Eff(k)+Z4_FL(k)+j*X3Eff));
Z2_FL(k)=(R1Eff(k)*(Z3_FL(k)+j*X2Eff)/(R1Eff(k)+Z3_FL(k)+j*X2Eff));
Z1_FL(k)=(Z2_FL(k) + j*X1Eff);
Z0_FL(k)=((Z1_FL(k)*(j*XmEff_FL))/(Z1_FL(k)+j*XmEff_FL));
RrEff_FL_SE(k)=real(Z1_FL(k))*Seff_F(k);

%Equivalent calculation equation
ZinEff_FL(k) = RsEff_FL+j*XsEff_FL+Z0_FL(k);
ZinEff_FL_abs(k)=abs(ZinEff_FL(k));
IsEff_FL(k)=harmonicEff(k)/(ZinEff_FL_abs(k));
IsEff_FL_AMPS(k) = IsEff_FL(k)*Ibase;
PFEff_FL(k)=cos(angle(ZinEff_FL(k)));
PinEff_F(k)= powHarmonic(k)*IsEff_FL(k)*PFEff_FL(k);
PinEff_FW(k)=PinEff_F(k) *pBase;

% Stator loss
PsEff_FL(k)=(IsEff_FL(k))^2*(RsEff_FL);

% Rotor loss
IrEff_FL(k) = IsEff_FL(k)*abs(j*XmEff_FL/(j*XmEff_FL+Z0_FL(k)));
PrEff_FL(k)=(IrEff_FL(k))^2*real(Z1_FL(k));
% Pm = (IsEff_FL)^2*real(Z0_FL);
% PrEff_FL(k)=Pm*Seff_F(k);

% Calculate Losses
PEff_FL_LossW = PEff_FL_Loss/pBase;
PEff_NL_LossW = PEff_NL_Loss/pBase;
if k < 2
    PoutEff_F(k)=PinEff_F(k)-PEff_FL_LossW;
    tLossEff(k) = PEff_FL_LossW;
else
    pLoss1(k) = 0.01*PinEff_F(k);
    pLossEff(k) = pLoss1(k);
    PoutEff_F(k)=PinEff_F(k)-(PsEff_FL(k)+PrEff_FL(k)+PEff_NL_LossW+pLossEff(k));
    tLossEff(k) = PsEff_FL(k)+PrEff_FL(k)+PEff_NL_LossW+pLossEff(k);
end

% Calculate Efficiency
effEff(k) =(PoutEff_F/PinEff_F)*100;
pause(1)
end

for k = 1:length(harmonicOrder);
    harmonicStd(k)=1/harmonicOrder(k);

```

```

powHarmonic(k)=1/harmonicOrder(k);
Sstd_F(k) = slipArrayStd(k);

% Calculate Skin Effect model values
% Rotor Resistances
R1Std(k)=RrStd_FL/((0.1)*Sstd_F(k));
R2Std(k)=RrStd_FL/((0.2)*Sstd_F(k));
R3Std(k)=RrStd_FL/((0.3)*Sstd_F(k));
R4Std(k)=RrStd_FL/((0.4)*Sstd_F(k));

% Calculate Skin effect model values
RrStd_NEG_FL=(RrStd_LR-RrStd_FL)*(2-Sstd_FL)+RrStd_FL;

% Internal Inductance of Rotor bar LiiStd
LiiStd=(RrStd_NEG_FL)^2/RrStd_FL;

% External Inductance (Gap) of Rotor bar Xg
XGStd = XrStd_FL-LiiStd/3;

% Rotor Inductances
L1Std=LiiStd*0.1;
L2Std=LiiStd*0.2;
L3Std=LiiStd*0.3;
L4Std=LiiStd*0.4;

X1Std=XGStd+L1Std/2;
X2Std=L1Std/2+L2Std/2;
X3Std=L2Std/2+L3Std/2;
X4Std=L3Std/2+L4Std/2;

% Equivalent Circuit Calculation for Fundamental
Z4_FL(k)=(R3Std(k)*(R4Std(k)+j*X4Std)/(R3Std(k)+R4Std(k)+j*X4Std);
Z3_FL(k)=(R2Std(k)*(Z4_FL(k)+j*X3Std)/(R2Std(k)+Z4_FL(k)+j*X3Std));
Z2_FL(k)=(R1Std(k)*(Z3_FL(k)+j*X2Std)/(R1Std(k)+Z3_FL(k)+j*X2Std));
Z1_FL(k)=(Z2_FL(k) + j*X1Std);
Z0_FL(k)=((Z1_FL(k)*(j*XmStd_FL))/(Z1_FL(k)+j*XmStd_FL));

RrStd_FL_SE(k)=real(Z1_FL(k))*Seff_F(k);

% Equivalent calculation equation
ZinStd_FL(k) = RsStd_FL+j*XsStd_FL+Z0_FL(k);
ZinStd_FL_abs(k)=abs(ZinStd_FL(k));
IsStd_FL(k)=harmonicStd(k)/(ZinStd_FL_abs(k));
IsStd_FL_AMPS(k) = IsStd_FL(k)*Ibase;
PFStd_FL(k)=cos(angle(ZinStd_FL(k)));
PinStd_F(k)=powHarmonic(k)*IsStd_FL(k) *PFStd_FL(k);
PinStd_FW(k)=PinStd_F(k) *pBaseStd;

% Stator loss
PsStd_FL(k)=(IsStd_FL(k))^2*(RsStd_FL);

```

```

% Rotor loss
IrStd_FL(k) = IsStd_FL(k)*abs(j*XmStd_FL/(j*XmStd_FL+Z0_FL(k)));
PrStd_FL(k)=(IrStd_FL(k))^2*real(Z1_FL(k));
% Pm = (IsStd_FL)^2*real(Z0_FL);
% PrStd_FL(k)=Pm*Seff_F(k);
% Calculating Losses
PStd_FL_LossW = PStd_FL_Loss/pBaseStd;
PStd_NL_LossW = PStd_NL_Loss/pBaseStd;
if k < 2
    PoutStd_F(k)=PinStd_F(k)-PStd_FL_LossW;
    tLossStd(k) = PStd_FL_LossW;
else
    pLoss1(k) = 0.01*PinStd_F(k);
    pLossStd(k) = pLoss1(k);
    PoutStd_F(k)=PinStd_F(k) -(PsStd_FL(k)+PrStd_FL(k)+PStd_NL_LossW+pLossStd(k));
    tLossStd(k) = PsStd_FL(k)+PrStd_FL(k)+PStd_NL_LossW+pLossStd(k);
end
% Calculate Efficiency
effStd(k) =(PoutStd_F/PinStd_F)*100;
pause(1)
end

% Calculate Cost Savings
for b = 1:length(harmonicOrder);
    lifeCostSaving(b) = 0.746*horsePower*percentOper*runTime*elecCost*((100/effStd(b))-
(100/effEff(b)));
    PBP(b) = (abs(EEMCost - STMCost))/lifeCostSaving(b);
end

fprintf('EEM Stator Loss \n');
fprintf('%g \n',PsEff_FL);
fprintf('EEM Rotor Loss \n');
fprintf('%g \n', PrEff_FL);
fprintf('EEM Eff \n');
fprintf('%g \n',effEff);
fprintf('EEM tLoss \n');
fprintf('%g \n',tLossEff);

fprintf('STM Stator Loss \n');
fprintf('%g \n',PsStd_FL);
fprintf('STM Rotor Loss \n');
fprintf('%g \n', PrStd_FL);
fprintf('STM Eff \n');
fprintf('%g \n',effStd);
fprintf('STM tLoss \n');
fprintf('%g \n',tLossStd);

fprintf('LifeCost \n');
fprintf('%g \n',lifeCostSaving);
fprintf('PBP \n');
fprintf('%g \n',PBP);

```

```
figure
plot(harmonicOrder,effStd,'r+:', harmonicOrder,effEff,'bd-' )
title('Motor Efficiencies Vs. Harmonic Order ')
xlabel('Harmonic Level')
ylabel('Efficiency')
```

APPENDIX B

MOTOR DATA

General Data: Data for 25HP EEM

Horse Power:	25
Speed:	1800 RPM
Voltage:	265
Efficiency:	93.4
Power Factor:	85.90%
Sfl	0.014

General Data: Data for 25HP STM

Horse Power:	25
Speed:	1800 RPM
Voltage:	460
Efficiency:	90.7
Power Factor:	89.40%
Sfl	0.0194

	Full Load (pu)
Rs	0.0246
Xs	0.1122
Rr/s	0.9935
Rr=Rr/s*s	0.0139
Xr	0.1787
Xm	3.4275

	Full Load (pu)
Rs	0.0342
Xs	0.1063
Rr/s	0.9740
Rr=Rr/s*s	0.0189
Xr	0.1498
Xm	4.0682

General Data: Data for 50HP EEM

Horse Power:	50
Speed:	1800 RPM
Voltage:	460
Efficiency:	94.1
Power Factor:	88.30%
Sfl	0.014

General Data: Data for 50HP STM

Horse Power:	50
Speed:	1800 RPM
Voltage:	132
Efficiency:	92.4
Power Factor:	88.60%
Sfl	0.0144

	Full Load (pu)
Rs	0.0239
Xs	0.1097
Rr/s	0.9823
Rr=Rr/s*s	0.0138
Xr	0.1665
Xm	4.0697

	Full Load (pu)
Rs	0.0270
Xs	0.1152
Rr/s	0.9707
Rr=Rr/s*s	0.0140
Xr	0.1723
Xm	4.3753

General Data: Data for 100HP EEM

Horse Power: 100
 Speed: 1800 RPM
 Voltage: 460
 Efficiency: 95.4
 Power Factor: 0.870
 Sfl 0.0087

Full Load (pu)

Rs 0.0137
 Xs 0.1130
 Rr/s 1.0057
 Rr=Rr/s*s 0.0087
 Xr 0.1392
 Xm 3.3586

General Data: Data for 100HP STM

Horse Power: 100
 Speed: 1800 RPM
 Voltage: 460
 Efficiency: 93
 Power Factor: 0.862
 Sfl 0.0094

Full Load (pu)

Rs 0.0148
 Xs 0.1249
 Rr/s 0.9974
 Rr=Rr/s*s 0.0094
 Xr 0.1482
 Xm 3.3892

General Data: Data for 150HP EEM

Horse Power: 150
 Speed: 1800 RPM
 Voltage: 460
 Efficiency: 95.7
 Power Factor: 0.854
 Sfl 0.0092

Full Load (pu)

Rs 0.0123
 Xs 0.1187
 Rr/s 0.9992
 Rr=Rr/s*s 0.0092
 Xr 0.1851
 Xm 3.5438

General Data: Data for 150HP STM

Horse Power: 150
 Speed: 1800 RPM
 Voltage: 460.00
 Efficiency: 93.7
 Power Factor: 0.878
 Sfl 0.0109

Full Load (pu)

Rs 0.0159
 Xs 0.1349
 Rr/s 0.9759
 Rr=Rr/s*s 0.0106
 Xr 0.1511
 Xm 4.1032

General Data: Data for 200HP EEM

Horse Power: 200
 Speed: 1800 RPM
 Voltage: 460
 Efficiency: 95.9
 Power Factor: 0.863
 Sfl 0.0094

Full Load (pu)

Rs 0.0111
 Xs 0.1171
 Rr/s 0.9930
 Rr=Rr/s*s 0.0093
 Xr 0.1899
 Xm 3.8879

General Data: Data for 200HP STM

Horse Power: 200
 Speed: 1800 RPM
 Voltage: 460
 Efficiency: 94.6
 Power Factor: 0.888
 Sfl 0.0101

Full Load (pu)

Rs 0.0137
 Xs 0.1193
 Rr/s 0.9888
 Rr=Rr/s*s 0.0100
 Xr 0.1504
 Xm 4.2500

General Data: Data for 250HP EEM

Horse Power: 250
 Speed: 1800 RPM
 Voltage: 796.74
 Efficiency: 96.2
 Power Factor: 0.886
 Sfl 0.0081

Full Load (pu)

Rs 0.0108
 Xs 0.1331
 Rr/s 0.9784
 Rr=Rr/s*s 0.0079
 Xr 0.1441
 Xm 4.3604

General Data: Data for 250HP STM

Horse Power: 250
 Speed: 1800 RPM
 Voltage: 796.74
 Efficiency: 94.3
 Power Factor: 0.878
 Sfl 0.0085

Full Load (pu)

Rs 0.0126
 Xs 0.1462
 Rr/s 0.9713
 Rr=Rr/s*s 0.0083
 Xr 0.1425
 Xm 4.1623

General Data: Data for 300HP EEM

Horse Power: 300
 Speed: 1800 RPM
 Voltage: 400
 Efficiency: 96.5
 Power Factor: 89.50%
 Sfl 0.0082

Full Load (pu)

Rs 0.0104
 Xs 0.1251
 Rr/s 0.9783
 Rr=Rr/s*s 0.0080
 Xr 0.1466
 Xm 4.7147

General Data: Data for 300HP STM

Horse Power: 300
 Speed: 1800 RPM
 Voltage: 400.00
 Efficiency: 94.9
 Power Factor: 88.70%
 Sfl 0.0088

Full Load (pu)

Rs 0.0115
 Xs 0.1396
 Rr/s 0.9720
 Rr=Rr/s*s 0.0086
 Xr 0.1452
 Xm 4.5359

VITA

Oladokun Emmanuel Faduyile was born in Okitipupa, Ondo State , Nigeria, West Africa on March 2, 1977. He was raised in Okitipupa, Ondo State, Nigeria and went to St. Johns Primary School and Stella Maris College in Okitipupa. He graduated from Stella Maris College in 1993. From there, he went to Adeyemi College of Education and later to University of Tennessee, Chattanooga and received a B. Sc in Electrical Engineering and minor in mathematics in 2004.

Oladokun is currently pursuing his master degree in electrical engineering with concentration in Power System at University of Tennessee, Chattanooga, TN.