MOTOR CHARACTERISTIC CURVE MODELING DURING CURRENT LIMIT STARTING USING SOLID STATE CONTROLS.

And Comparison with Across The Line Starting (ATL) Methods.

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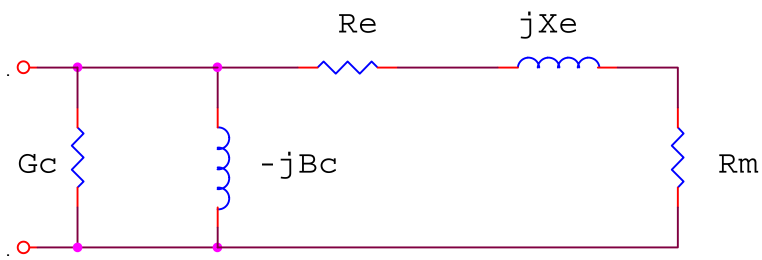
I INTRODUCTION -

The standard 3 phase AC induction motor consists of a stator that is electrically connected through some starting method to the 3 phase line power and a rotor that is mechanically connected through the shaft to the mechanical load. Depending on the construction of the motor, it has various torque, current, and horse power values at various amounts of slip. NEMA standard MG-10 defines some standard torque speed curves (see attached figure). These standard torque speed curves assume full voltage across the motor terminals throughout the speed range. This is the characteristic curve when starting a motor across the line with a contactor or motor starter. As soon as the contactor pulls in, line voltage (minus line voltage drop) is placed directly across the starter. During a current limit softstart, the applied voltage is reduced to limit current. This changes the characteristic motor torque speed curve since the voltage at the motor terminals is not constant but varies as the motor approaches operational speed. This paper uses curve fitting techniques to generate the standard ATL torque slip curves for NEMA Design B, C, D, and E motors. Then, knowing that at any given rotor speed, the current to the windings of the motor is directly proportional to the voltage applied to the motor windings. Since we have the standard ATL motor currents at various speeds, we can use this relationship to find the currents and voltages at various speeds for a current limit start. Next, knowing that, at any given speed, torque is proportional to the square of the voltage applied to the stator, we can define the torque available at the motor during a current limit start. Lastly, knowing that power is directly proportional to the product of torque and speed, we can generate the power speed curve.

II ELECTRICAL THEORY OF MOTOR OPERATION -

The general single line equivalent model for the standard three phase AC induction motor is shown below:

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WHERE:
Re = rs + a*a*rr
Xe = xs + a*a*xr
Rm = ((1-S)/S) *a*a*rr
```

Figure #1 : Symbolic Representation Motor Electrical Characteristics.

Evaluating this single line model for the motor, the power transferred to the shaft of the motor is the product of the torque developed at the shaft of the motor and the speed of the rotor. This can be represented by the following equation:

$$Pm = T * Ur$$

Where:
Pm = power at the shaft of the motor
T = torque on the shaft of the motor
Ur = motor rotor velocity

The torque developed in the shaft of the motor is proportional to the square of the voltage applied to the motor and is also effected by the slip of the motor as shown below:

$$T = \frac{sq(Vln)}{Us} * \frac{(((sq(a)*Rr)/S)/(sq(Rs+(sq(a)Rr)/S)+sq(Xe)))}{(sq(Rs+(sq(a)Rr)/S)+sq(Xe))}$$

The relationship between rotor speed and stator rotational frequency is:

$$Ur = Us*(1-S)$$

Where:
Ur = motor rotor velocity
Us = stator rotational field speed
S = slip of the motor

The slip of the motor is defined as the difference between the stator rotational field speed and the rotor velocity normalized to the stator rotational field speed. This is mathematically shown below as:

$$S = (Us - Ur)/Us$$

In order to evaluate the electrical and mechanical characteristics during starting, we can first look at the condition of the motor rotor being stopped. Note that when the motor rotor is stopped, Ur = 0. This means that at zero rotor speed, the slip S = 1. This means the power delivered to the load at locked rotor is zero. The torque delivered to the load however is much higher. The locked rotor torque is defined as:

$$T = \frac{sq(Vln)}{Us} * \frac{(sq(a)*Rr)/(sq(Rs+sq(a)Rr)+sq(Xe))}{(sq(Rs+sq(a)Rr)+sq(Xe))}$$

II PRACTICAL MODELING OF MOTOR OPERATION DURING ATL STARTING-

The National Electronics Manufacturer Association (NEMA) has defined standards for several different styles of motor construction (see NEMA Standards MG 10 for further information). They have defined 5 different basic motor styles. These are defined by their speed / torque characteristics. The chart below provides a simple visual description of these 5 categories.

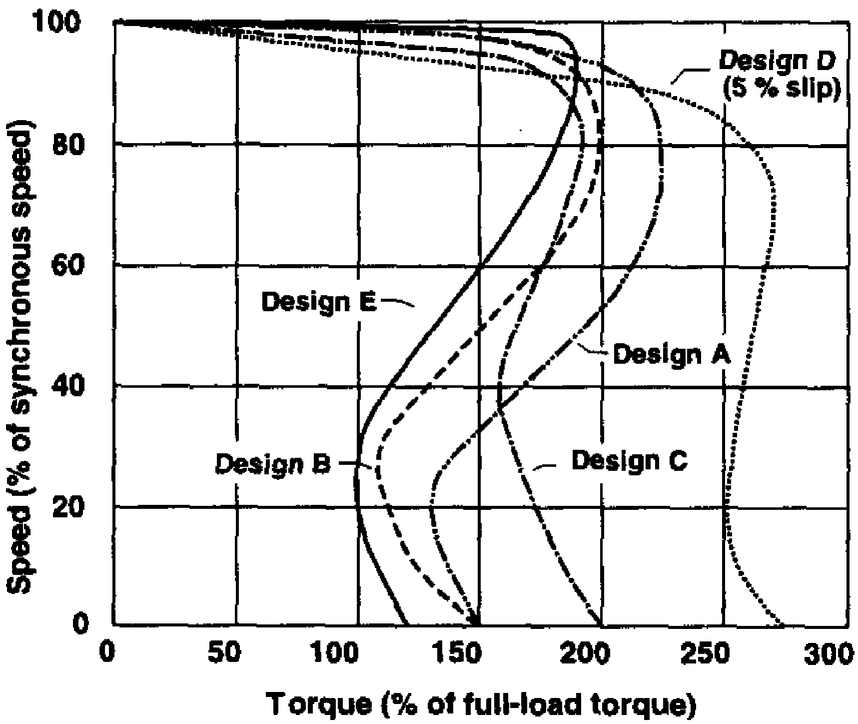


Figure #2 : Graphical Representation of Torque Vs. Speed for NEMA Design A Through E Motors.

Given these curves, we can use curve fitting techniques to generate an equation to give us the available torque for a certain slip speed. The general form for the equation is:

$$T = A * U^5 + B * U^4 + C * U^3 + D * U^2 + E * U + F$$

The following polynomials were found to be the best fit for the general equation given above:

CONSTANTS FOR NEMA DESIGN A MOTOR

ATA := - 45.57292	AIA := - 26.041666666
BTA := 95.052	BIA := 41.66666667
CTA := - 79.94792	CIA := - 28.125
DTA := 34.32292	DIA := 8.333333333
ETA := - 5.3542	EIA := - 1.833333333
FTA := 1.5	FIA := 6

CONSTANTS FOR NEMA DESIGN B MOTOR

ATB := - 32.53208	AIB := - 26.0416666667
BTB := 57.2917	BIB := 41.66666667
CTB := - 40.364583	CIB := - 28.125
DTB := 18.3333333	DIB := 8.333333333
ETB := - 4.2083333	EIB := - 1.833333333
FTB := 1.5	FIB := 6

CONSTANTS FOR NEMA DESIGN C MOTOR

ATC := - 32.552083	AIC := - 26.0416666667
BTC := 52.083333	BIC := 41.66666667
CTC := - 25.78125	CIC := - 28.125
DTC := 6.04167	DIC := 8.333333333
ETC := - 1.79167	EIC := - 1.833333333
FTC := 2	FIC := 6

CONSTANTS FOR NEMA DESIGN D MOTOR

ATD := - 58.59375	AID := - 26.0416666667
BTD := 121.09375	BID := 41.66666667
CTD := - 94.0104167	CID := - 28.125
DTD := 33.90625	DID := 8.333333333
ETD := - 5.145833	EID := - 1.833333333
FTD := 2.75	FID := 6

CONSTANTS FOR NEMA DESIGN E MOTOR

$ATE := -44.27083333$ $AIE := -36.4583333$

$BTE := 85.9375$ $BIE := 60.15625$

$CTE := -61.979167$ $CIE := -41.7708333$

$DTE := 22.8125$ $DIE := 12.71875$

$ETE := -3.7$ $EIE := -2.64583333$

$FTE := 1.2$ $FIE := 8$

Now using these above defined constants, we generate our 5 speed / torque curves equations for the 5 standard style of motors as shown below:

CALCLATION OF TORQUE CURVES FOR VARIOUS DESIGN MOTORS

$$TA_I := ATA \cdot (V_I)^5 + BTA \cdot (V_I)^4 + CTA \cdot (V_I)^3 + DTA \cdot (V_I)^2 + ETA \cdot V_I + FTA$$

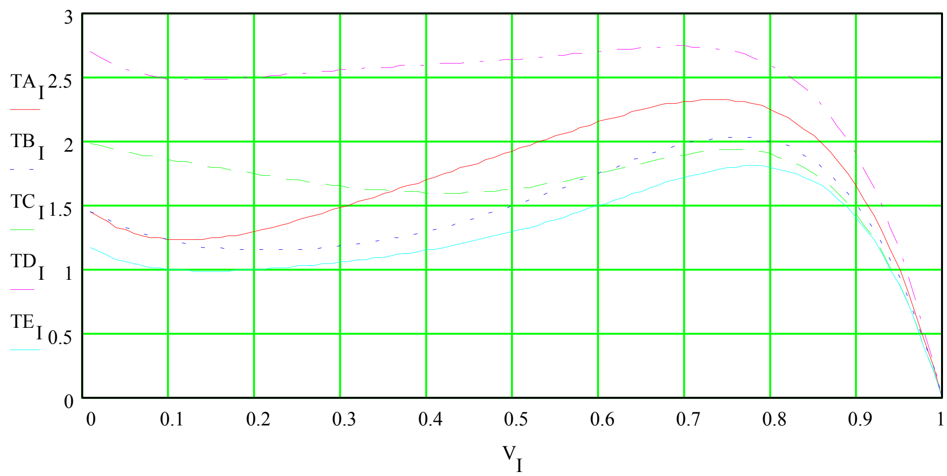
$$TB_I := ATB \cdot (V_I)^5 + BTB \cdot (V_I)^4 + CTB \cdot (V_I)^3 + DTB \cdot (V_I)^2 + ETB \cdot V_I + FTB$$

$$TC_I := ATC \cdot (V_I)^5 + BTC \cdot (V_I)^4 + CTC \cdot (V_I)^3 + DTC \cdot (V_I)^2 + ETC \cdot V_I + FTC$$

$$TD_I := ATD \cdot (V_I)^5 + BTD \cdot (V_I)^4 + CTD \cdot (V_I)^3 + DTD \cdot (V_I)^2 + ETD \cdot V_I + FTD$$

$$TE_I := ATE \cdot (V_I)^5 + BTE \cdot (V_I)^4 + CTE \cdot (V_I)^3 + DTE \cdot (V_I)^2 + ETE \cdot V_I + FTE$$

These 5 equations give us the following speed / torque curves:



GRAPHICAL REPRESENTATION OF GENERAL AC INDUCTION MOTOR TORQUE CHARACTERISTICS VS SPEED OF ROTOR AS NEMA DESIGN IS VARIED

Figure #3 : Graphical Representation of Torque Vs. Speed for NEMA Design A through E Motors Using Curve Fitting Techniques.

Close comparison of the calculated speed torque curves in Figure #3 with the speed torque curves defined in Figure #2 show a close correlation between the two. This is a very good check to ensure that the equations listed above closely approximate the actual motor speed / torque curves.

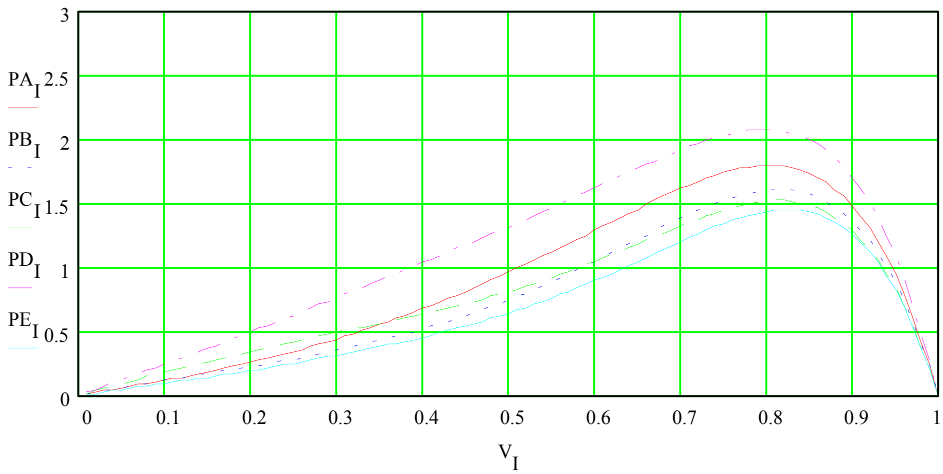
Next, we use the fact that the power available to the motor is equal to the product of the torque generated by the motor and the rotational speed of the rotor to define a speed / power curve for the standard motors. The powers are calculated below:

CALCULATION OF POWER CURVES FOR VARIOUS NEMA DESIGN MOTORS

$PA_I := V_I \cdot TA_I$ $\quad PB_I := V_I \cdot TB_I$

$PC_I := V_I \cdot TC_I$ $\quad PD_I := V_I \cdot TD_I$ $\quad PE_I := V_I \cdot TE_I$

These 5 equations give us the following speed / power curves:



GRAPHICAL REPRESENTATION OF GENERAL AC INDUCTION MOTOR POWER CHARACTERISTICS VS SPEED OF ROTOR AS NEMA DESIGN IS VARIED

Figure #4 : Graphical Representation of Power Vs. Speed for NEMA design A through E motors.

Lastly, we will want to model the relationship between current draw by the motor and the speed of the rotor. Current speed curves are given by motor manufacturers. A general representation is shown here. Following is the calculation of motor current vs. rotor speed:

CALCULATION OF CURRENT CURVES FOR VARIOUS NEMA DESIGN MOTORS

$$IA_I := AIA \cdot (V_I)^5 + BIA \cdot (V_I)^4 + CIA \cdot (V_I)^3 + DIA \cdot (V_I)^2 + EIA \cdot V_I + FIA$$

$$IB_I := AIB \cdot (V_I)^5 + BIB \cdot (V_I)^4 + CIB \cdot (V_I)^3 + DIB \cdot (V_I)^2 + EIB \cdot V_I + FIB$$

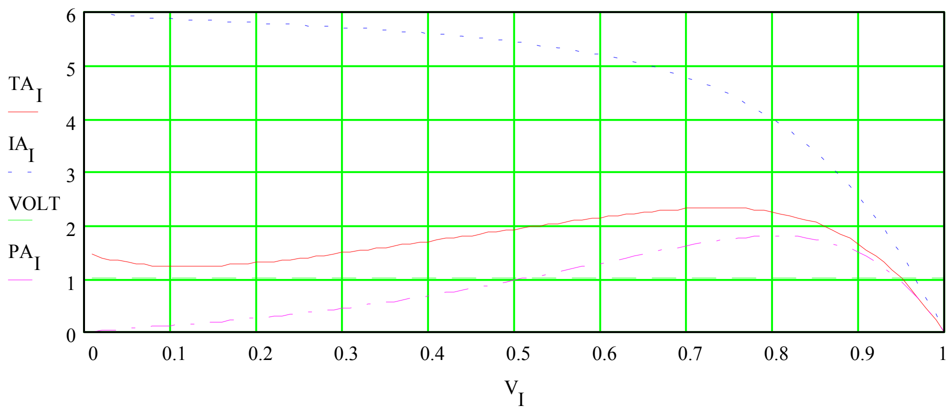
$$IC_I := AIC \cdot (V_I)^5 + BIC \cdot (V_I)^4 + CIC \cdot (V_I)^3 + DIC \cdot (V_I)^2 + EIC \cdot V_I + FIC$$

$$ID_I := AID \cdot (V_I)^5 + BID \cdot (V_I)^4 + CID \cdot (V_I)^3 + DID \cdot (V_I)^2 + EID \cdot V_I + FID$$

$$IE_I := AIE \cdot (V_I)^5 + BIE \cdot (V_I)^4 + CIE \cdot (V_I)^3 + DIE \cdot (V_I)^2 + EIE \cdot V_I + FIE$$

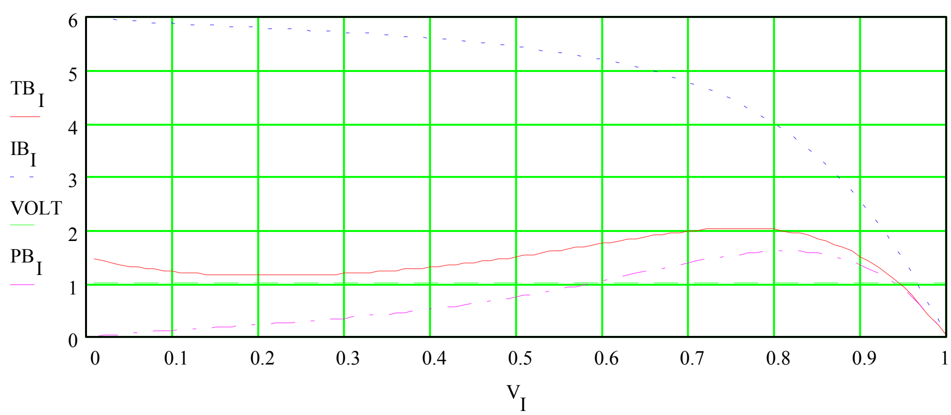
III ANALYSIS OF MODELING RESULTS FOR ATL STARTING METHODS-

Now that we have thoroughly modeled various NEMA style motors for speed / torque, speed / power, and speed / current characteristics, we display a graphical representation of our models below:



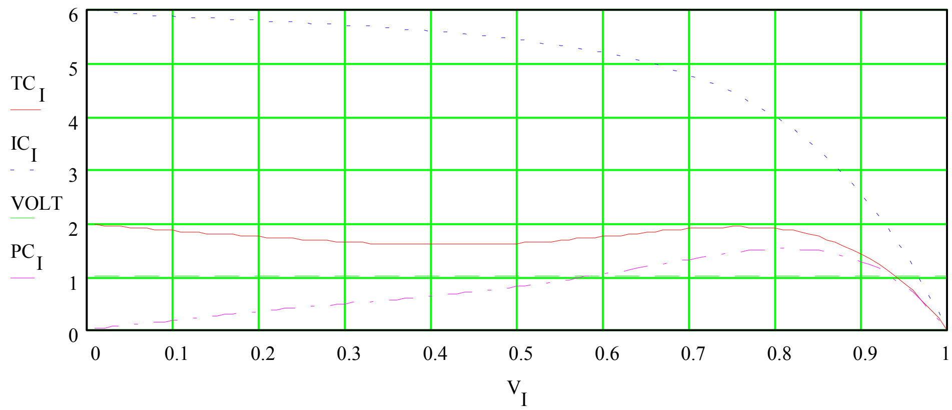
GRAPHICAL REPRESENTATION OF NEMA DEISGN A AC INDUCTION MOTOR CHARACTERISTICS VS SPEED OF ROTOR USING CONSTANT VOLTAGE ATL STARTING

Figure #5 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design A Motors.



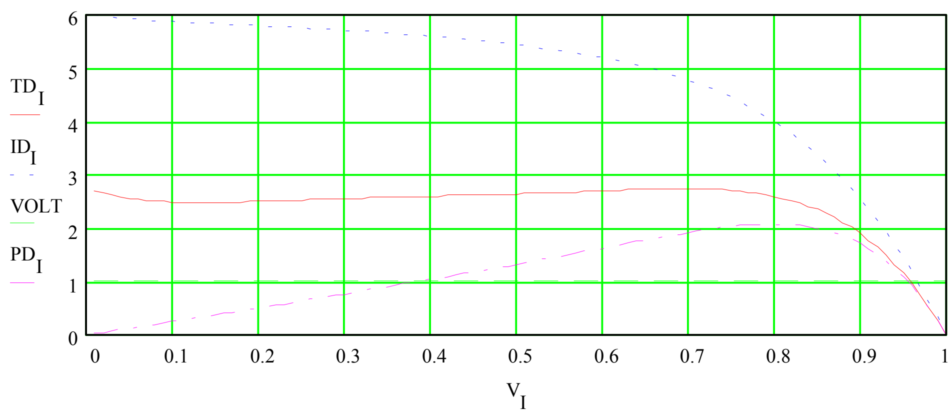
GRAPHICAL REPRESENTATION OF NEMA DESIGN B AC INDUCTION MOTOR CHARACTERISTICS VS SPEED OF ROTOR USING CONSTANT VOLTAGE ATL STARTING

Figure #6 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design B Motors.



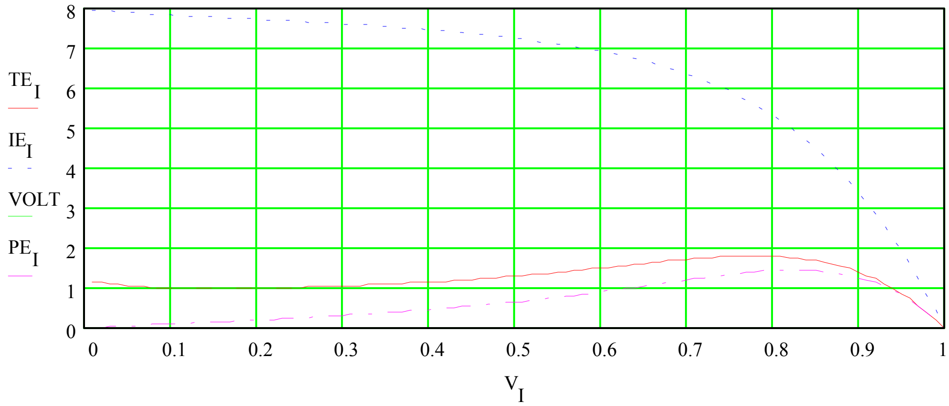
GRAPHICAL REPRESENTATION OF NEMA DESIGN C AC INDUCTION MOTOR CHARACTERISTICS VS SPEED OF ROTOR USING CONSTANT VOLTAGE ATL STARTING

Figure #7 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design C Motors.



GRAPHICAL REPRESENTATION OF NEMA DESIGN D AC INDUCTION MOTOR CHARACTERISTICS VS SPEED OF ROTOR USING CONSTANT VOLTAGE ATL STARTING

Figure #8 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design D Motors.



GRAPHICAL REPRESENTATION OF NEMA DESIGN E AC INDUCTION MOTOR CHARACTERISTICS VS SPEED OF ROTOR USING CONSTANT VOLTAGE ATL STARTING

Figure #9 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design E Motors.

IV PRACTICAL MODELING OF MOTOR OPERATION DURING CURRENT LIMIT STARTING-

Now that we have been able to derive mathematical equations for our various NEMA design motors and used them to find the speed / torque, speed / power, and speed / current curves, we can now turn our attention to what happens when the current to a motor is limited during starting.

During an ATL start, the voltage applied to the stator of the motor is constant and the properties of Torque, Current, and Power vary as the motor accelerates to full speed. With a solid state starter with current limit capability, the current is the electrical property held constant while the values of Torque, Voltage, and Power vary as determined by the current limit circuit. Knowing the motor characteristics during ATL starting and knowing the relationships between current and voltage, voltage and torque and torque/speed and power, we calculate below the corrections to the ATL starting curves. For generation of these curves, I assume the current limit setpoint is set to 3 times motor full load amps. If the current limit setpoint is any other value then ILIMIT in the calculation below must be modified.

$ILIMIT := 3$

$IRATIOA_I := \frac{IA_I}{ILIMIT}$ $\quad IRATIOB_I := \frac{IB_I}{ILIMIT}$

$IRATIOC_I := \frac{IC_I}{ILIMIT}$ $\quad IRATIOD_I := \frac{ID_I}{ILIMIT}$ $\quad IRATIOE_I := \frac{IE_I}{ILIMIT}$

$IRATIOA_I := if(IRATIOA_I < 1, 1, IRATIOA_I)$

$IRATIOB_I := if(IRATIOB_I < 1, 1, IRATIOB_I)$ $\quad IRATIOC_I := if(IRATIOC_I < 1, 1, IRATIOC_I)$

$IRATIOD_I := if(IRATIOD_I < 1, 1, IRATIOD_I)$ $\quad IRATIOE_I := if(IRATIOE_I < 1, 1, IRATIOE_I)$

$TAN_I := \frac{TA_I}{(IRATIOA_I)^2}$ $\quad IAN_I := \frac{IA_I}{IRATIOA_I}$ $\quad VAN_I := \frac{VOLT}{IRATIOA_I}$ $\quad PAN_I := TAN_I \cdot V_I$

$TBN_I := \frac{TB_I}{(IRATIOB_I)^2}$ $\quad IBN_I := \frac{IB_I}{IRATIOB_I}$ $\quad VBN_I := \frac{VOLT}{IRATIOB_I}$ $\quad PBN_I := TBN_I \cdot V_I$

$TCN_I := \frac{TC_I}{(IRATIOC_I)^2}$ $\quad ICN_I := \frac{IC_I}{IRATIOC_I}$ $\quad VCN_I := \frac{VOLT}{IRATIOC_I}$ $\quad PCN_I := TCN_I \cdot V_I$

$TDN_I := \frac{TD_I}{(IRATIOD_I)^2}$ $\quad IDN_I := \frac{ID_I}{IRATIOD_I}$ $\quad VDN_I := \frac{VOLT}{IRATIOD_I}$ $\quad PDN_I := TDN_I \cdot V_I$

$TEN_I := \frac{TE_I}{(IRATIOE_I)^2}$ $\quad IEN_I := \frac{IE_I}{IRATIOE_I}$ $\quad VEN_I := \frac{VOLT}{IRATIOE_I}$ $\quad PEN_I := TEN_I \cdot V_I$

V ANALYSIS OF MODELING RESULTS FOR CURRENT LIMIT STARTING METHODS-

Below are shown the calculated motor electrical characteristics for the various NEMA design motors for current limit starting.

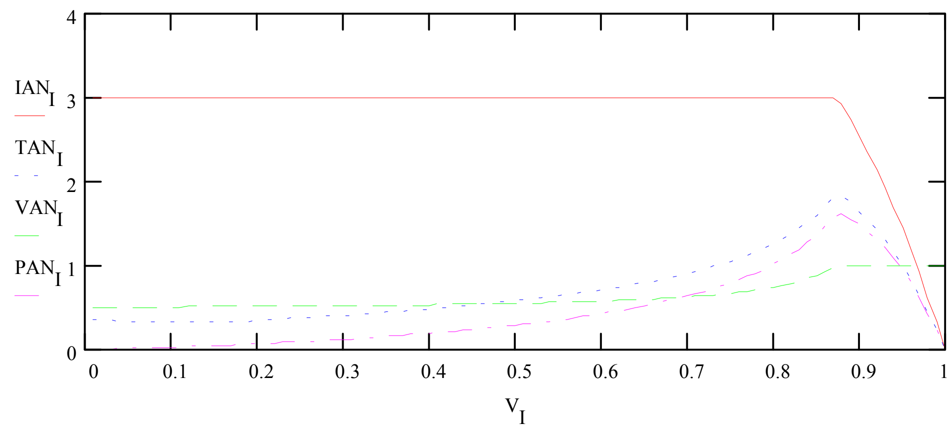


Figure #10 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design A Motors Under Current Limit Starting.

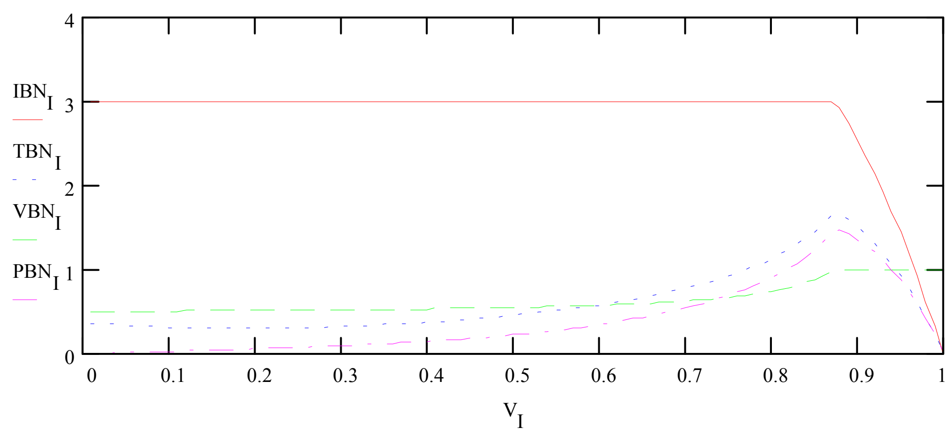


Figure #11 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design B Motors Under Current Limit Starting.

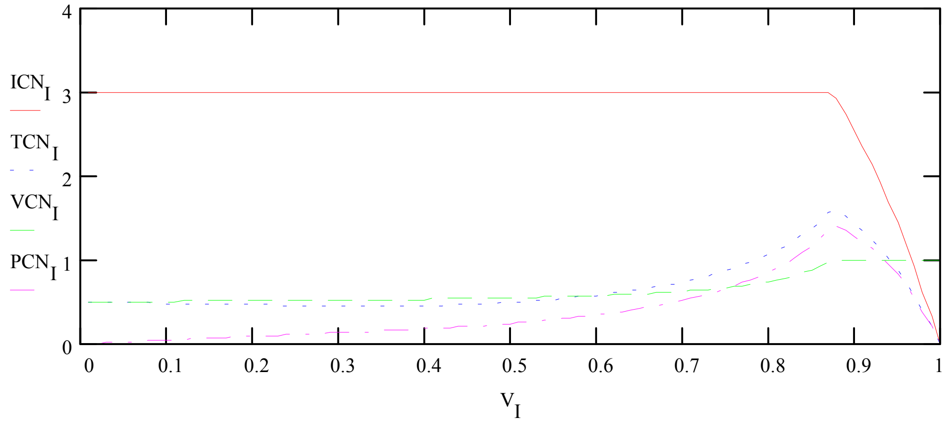


Figure #12 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design C Motors Under Current Limit Starting.

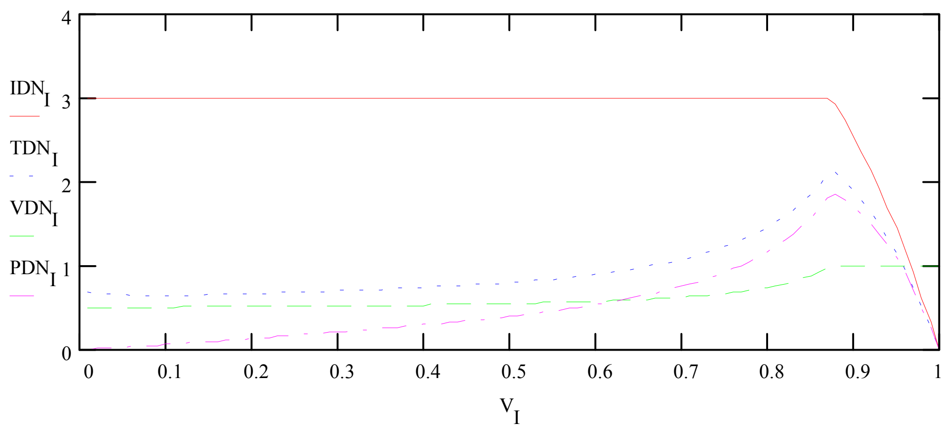


Figure #13 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design D Motors Under Current Limit Starting.

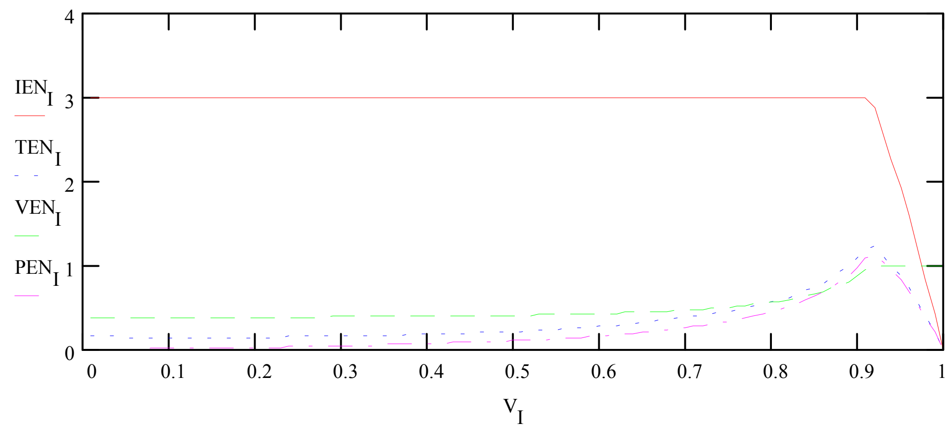


Figure #14 : Graphical Representation of Power Vs. Speed, Torque Vs. Speed, and Current Vs. Speed for NEMA Design E Motors Under Current Limit Starting.

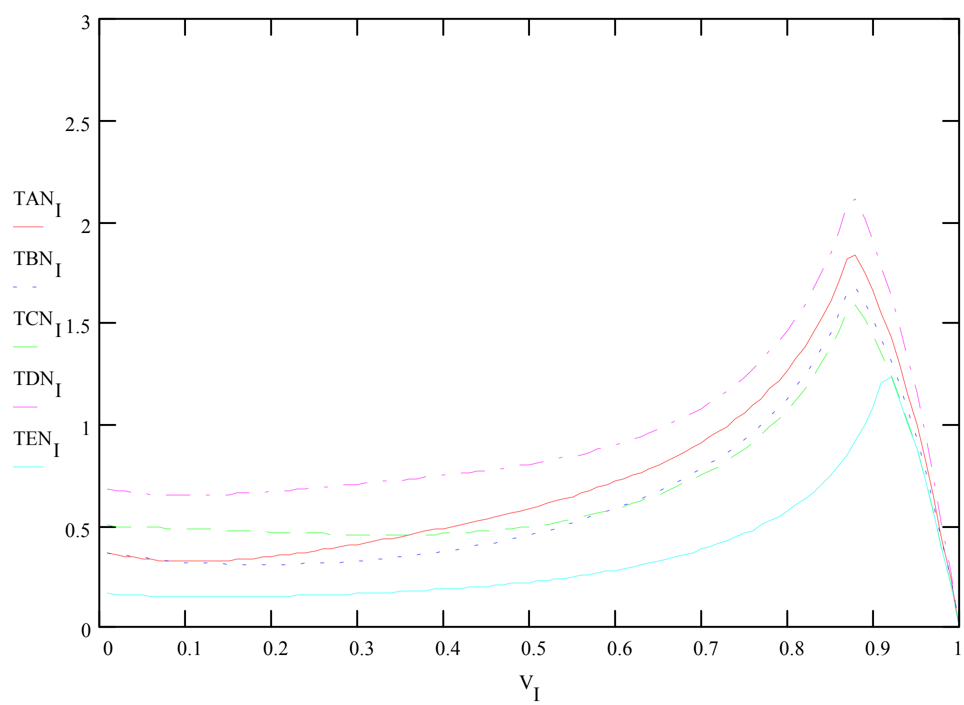


Figure #15 : Graphical Representation of Torque Vs. Speed for NEMA Design A, B, C, D, and E Motors Under Current Limit Starting.

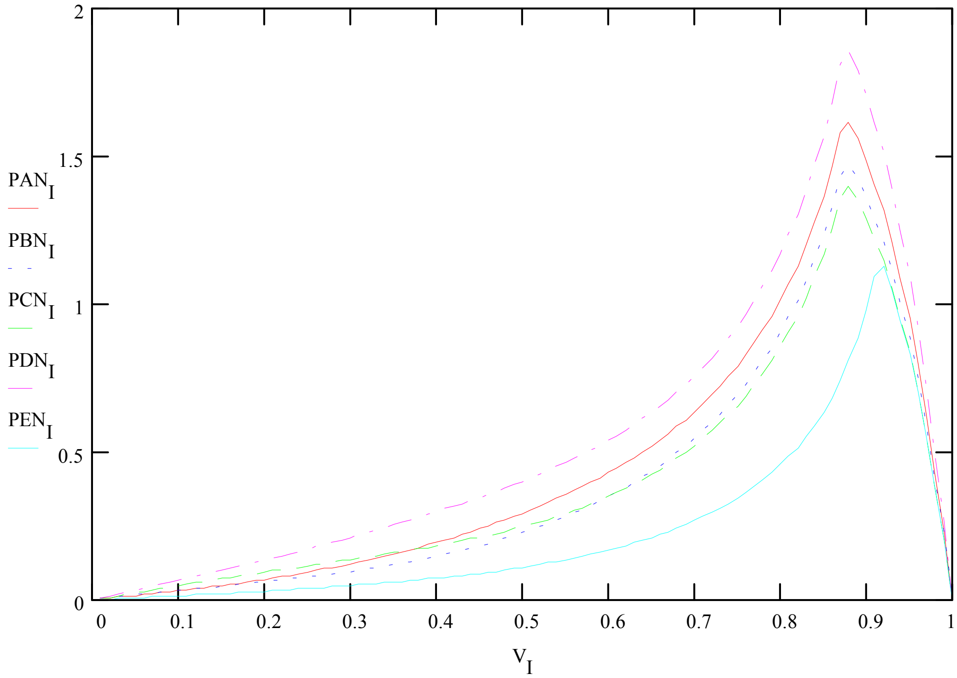


Figure #16 : Graphical Representation of Power Vs. Speed for NEMA Design A, B, C, D, and E Motors Under Current Limit Starting.

VI COMPARISON OF ATL STARTING METHODS VERSES CURRENT LIMIT STARTING METHODS AND THEIR EFFECTS ON MOTOR STARTING TORQUE, CURRENT, VOLTAGE, AND POWER CHARACTERISTICS-

Below are comparisons of motor electrical characteristics for both ATL starting and current limit starting methods.

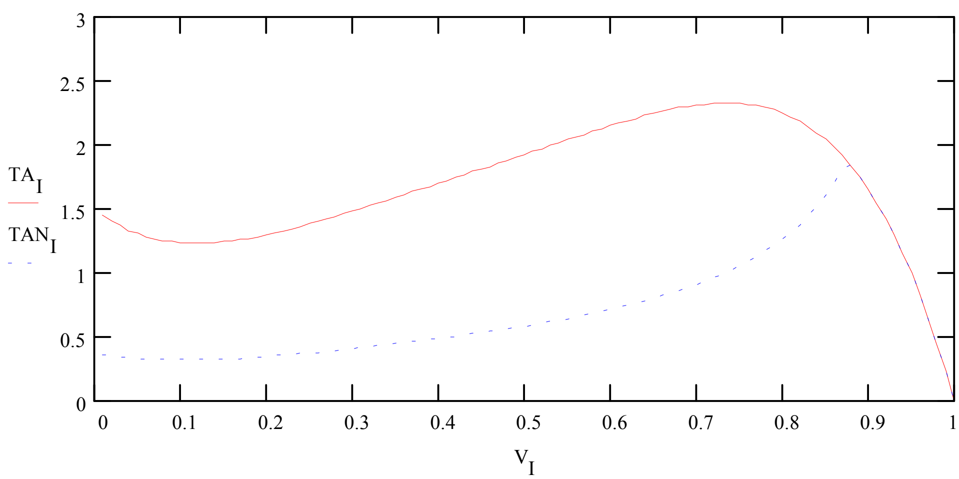


Figure #17 : Graphical Representation of Torque Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

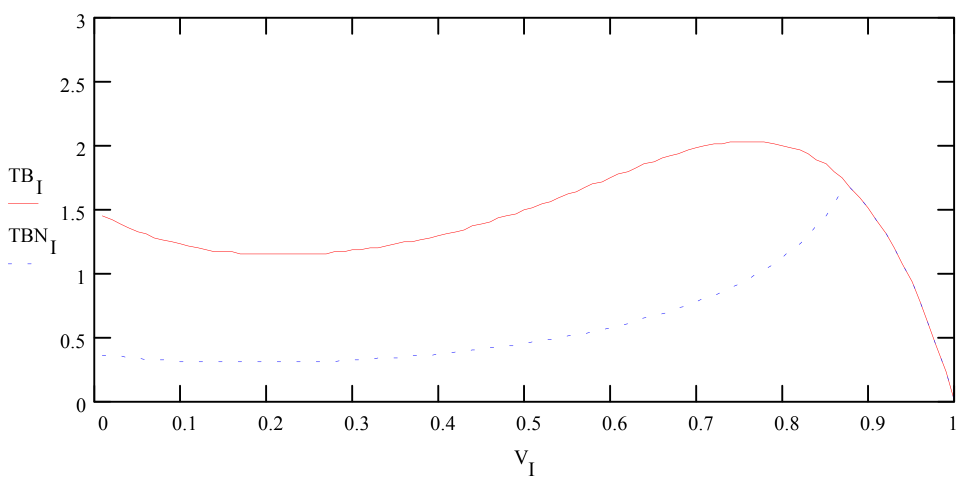


Figure #18 : Graphical Representation of Torque Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

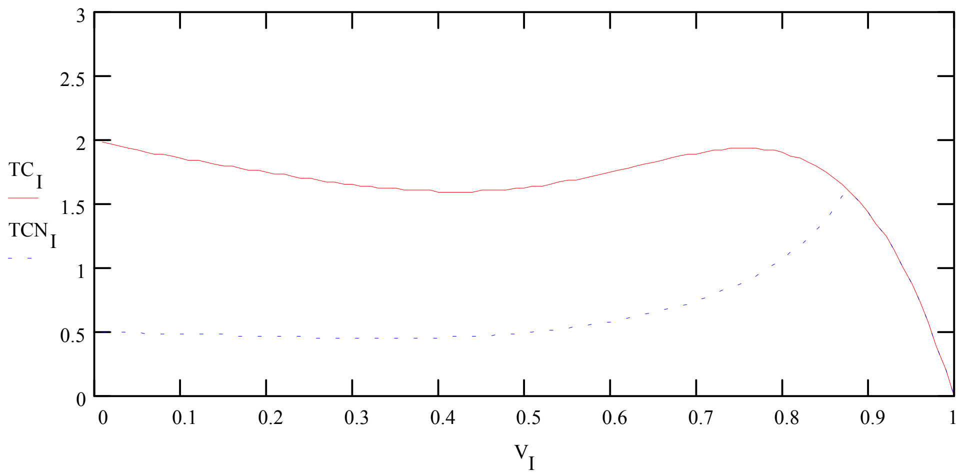


Figure #19 : Graphical Representation of Torque Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

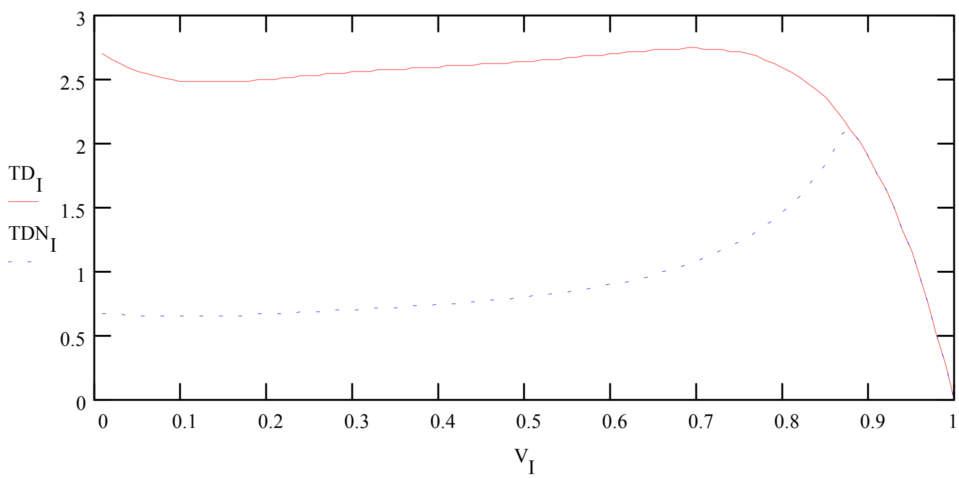


Figure #20 : Graphical Representation of Torque Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

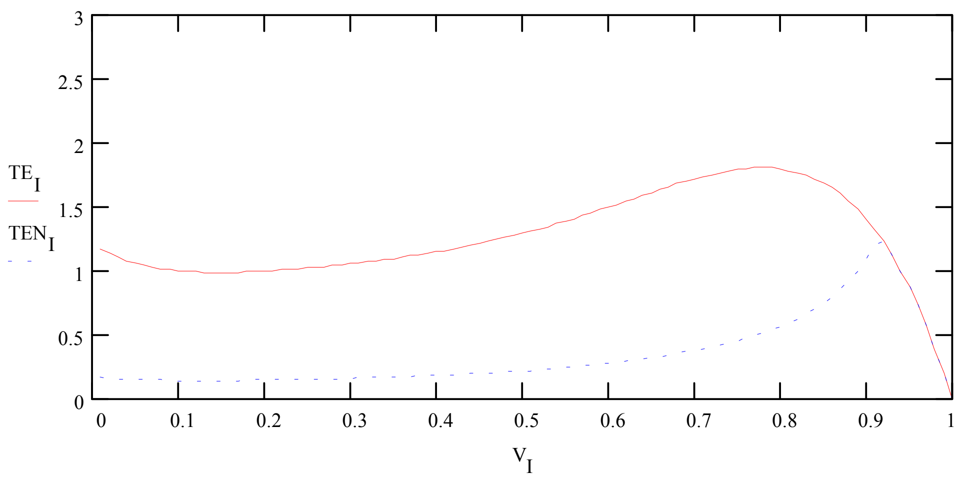


Figure #21 : Graphical Representation of Torque Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

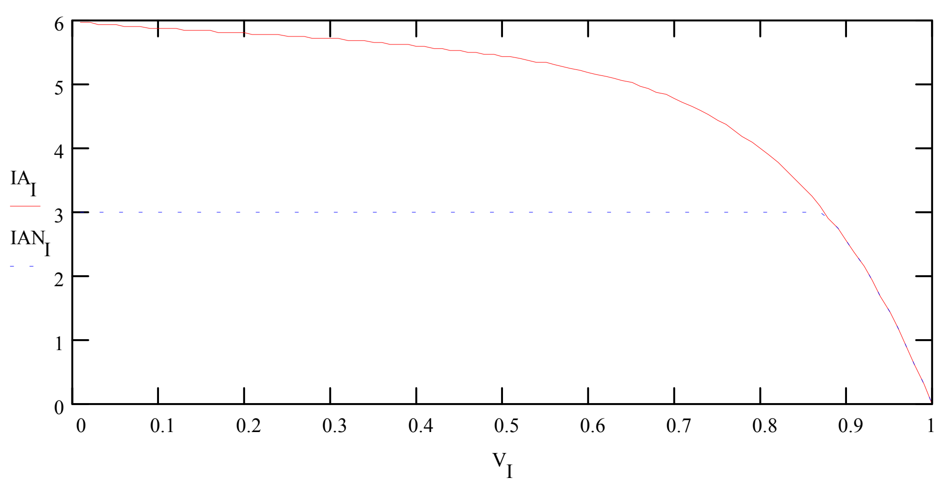


Figure #22 : Graphical Representation of Current Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

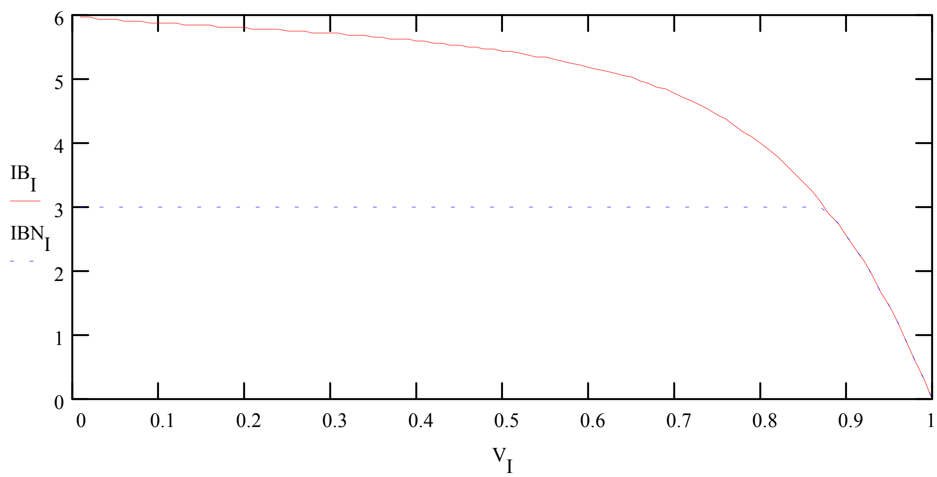


Figure #23 : Graphical Representation of Current Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

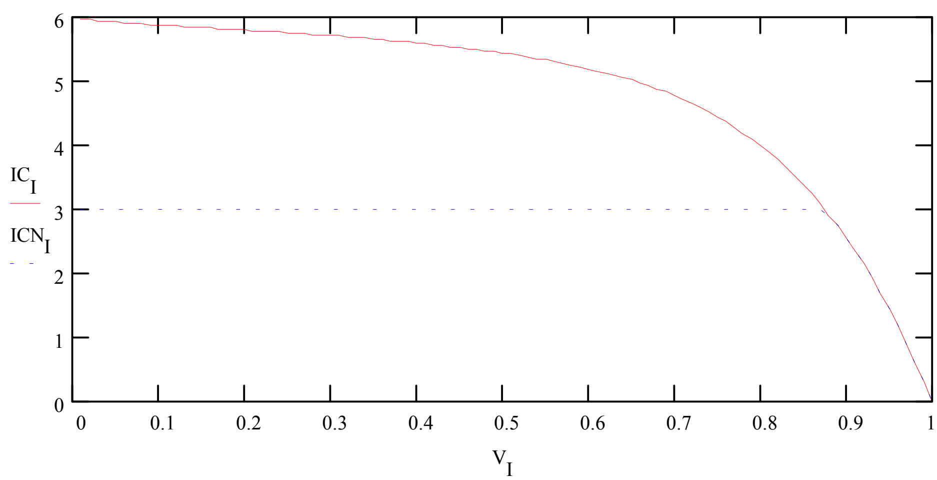


Figure #24 : Graphical Representation of Current Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

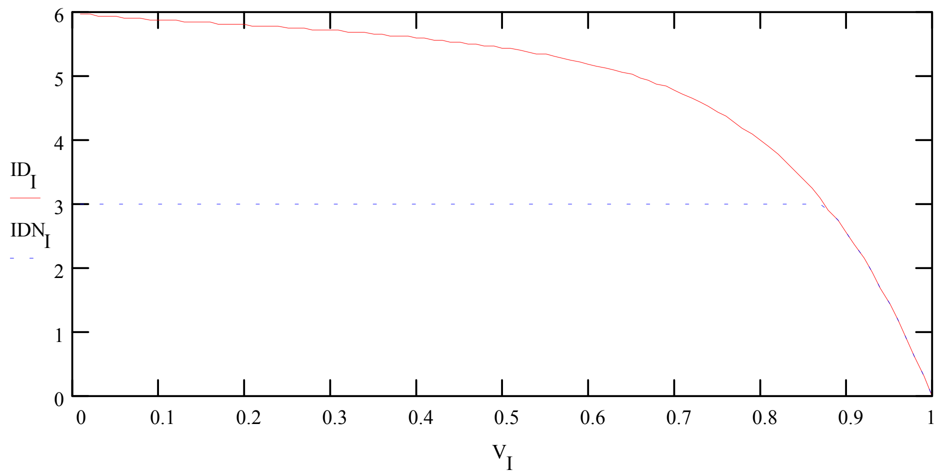


Figure #25 : Graphical Representation of Current Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

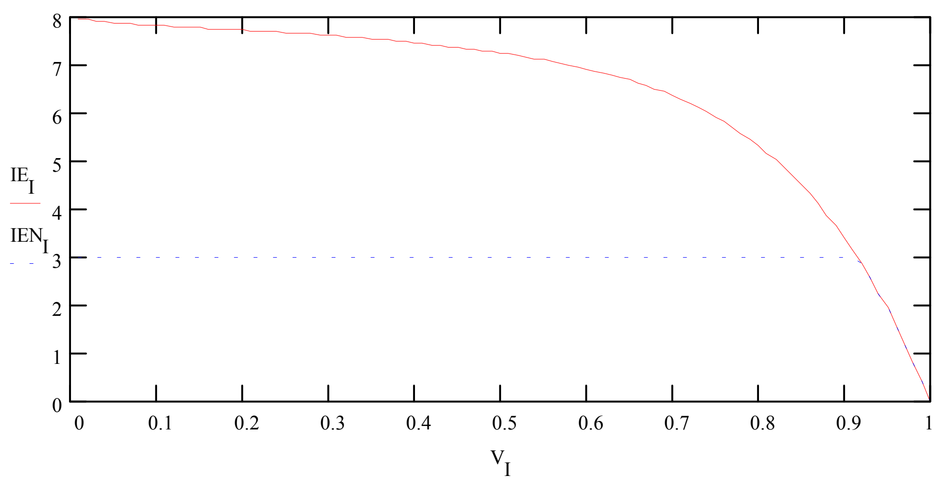


Figure #26 : Graphical Representation of Current Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

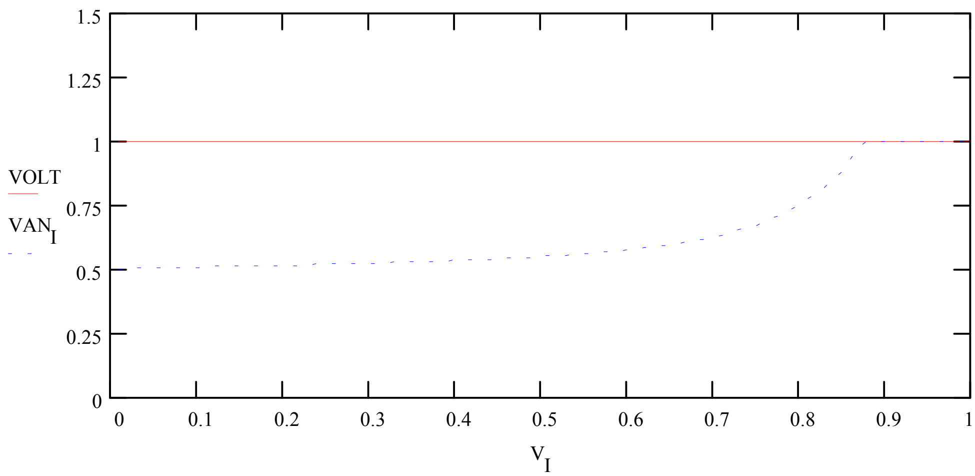


Figure #27 : Graphical Representation of Voltage Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

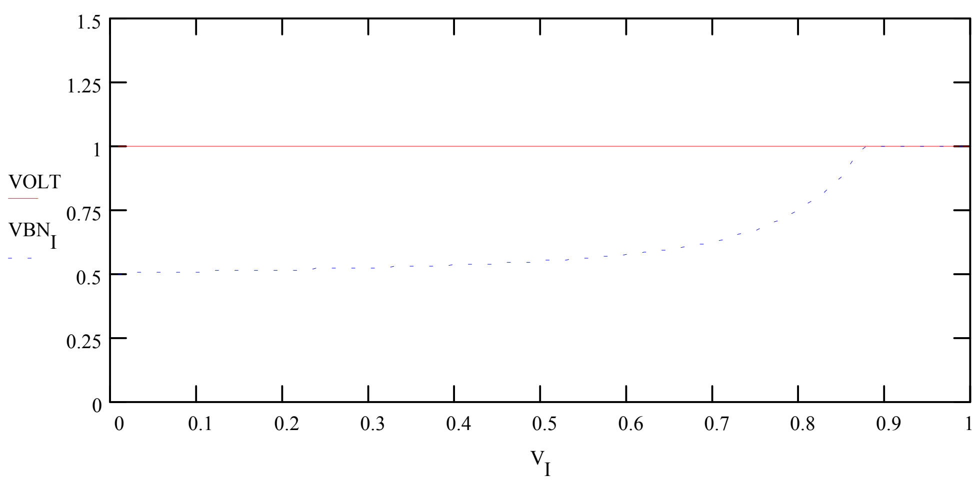


Figure #28 : Graphical Representation of Voltage Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

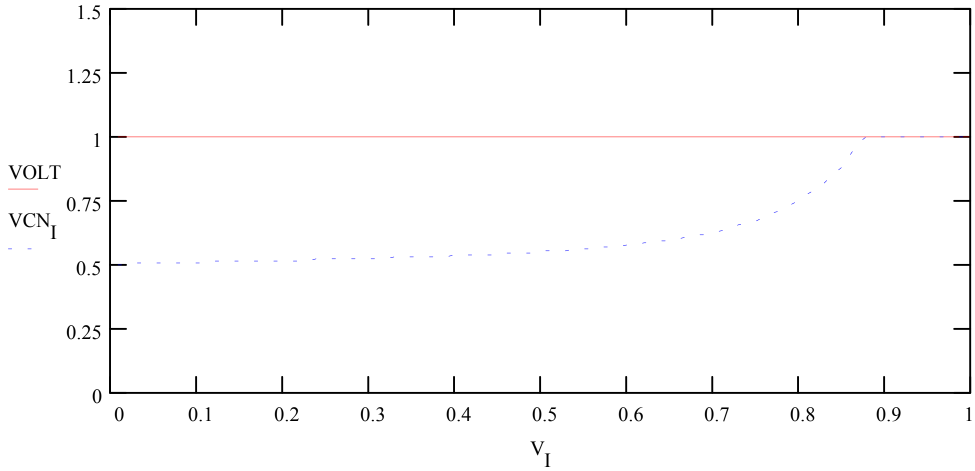


Figure #29 : Graphical Representation of Voltage Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

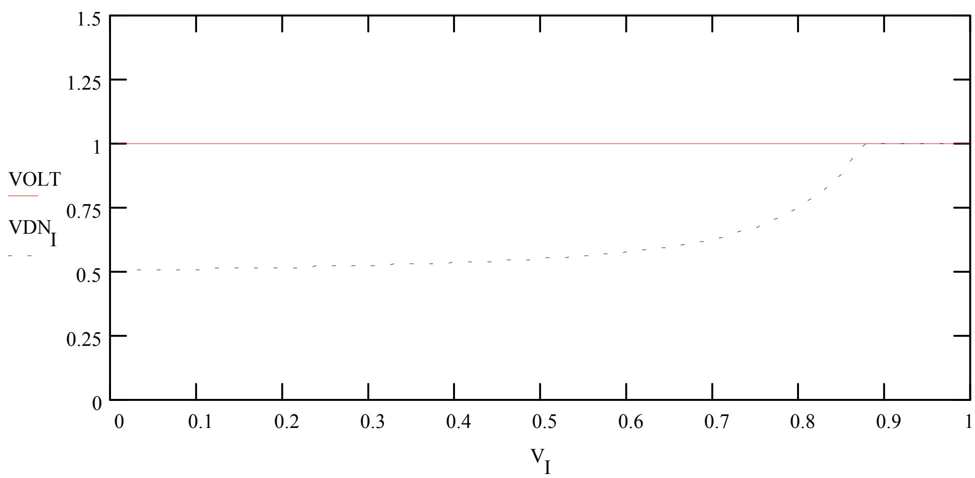


Figure #30 : Graphical Representation of Voltage Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

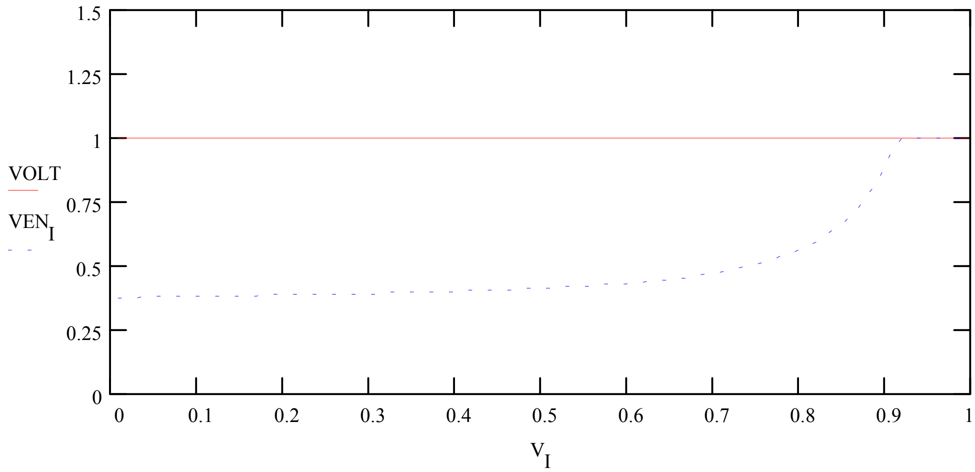


Figure #31 : Graphical Representation of Voltage Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

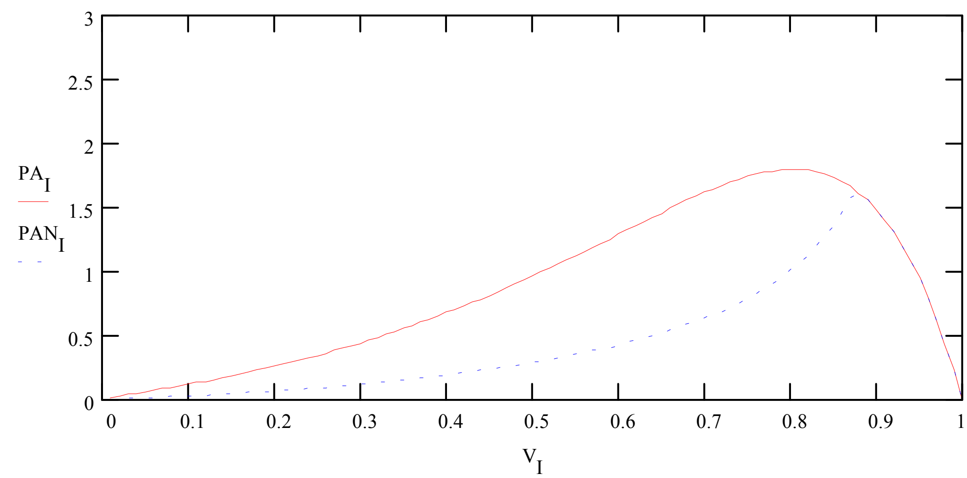


Figure #32 : Graphical Representation of Power Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

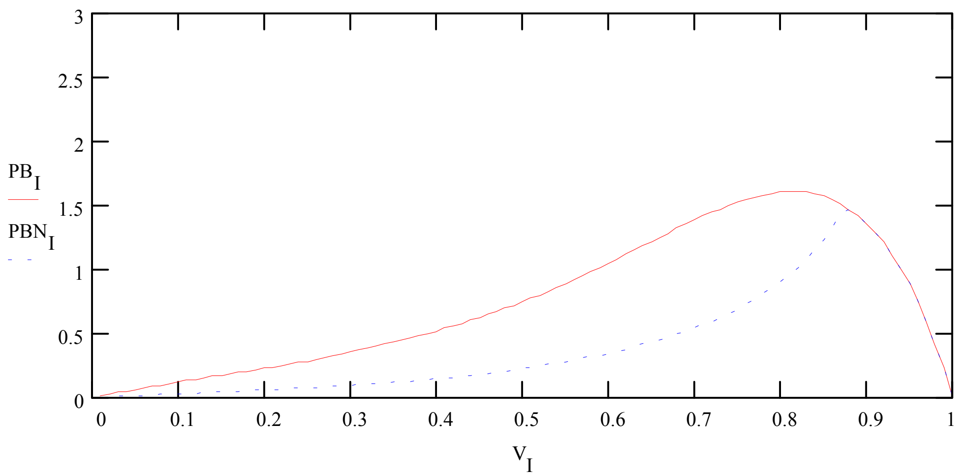


Figure #33 : Graphical Representation of Power Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

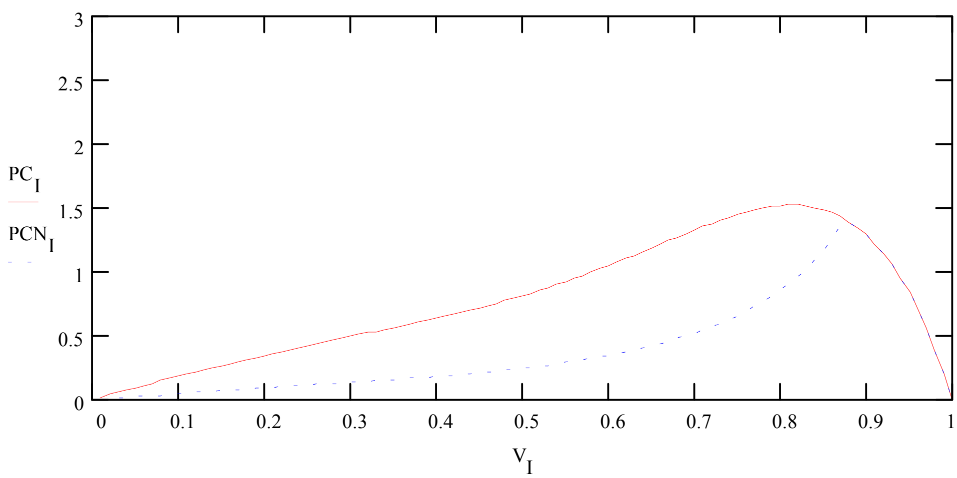


Figure #34 : Graphical Representation of Power Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

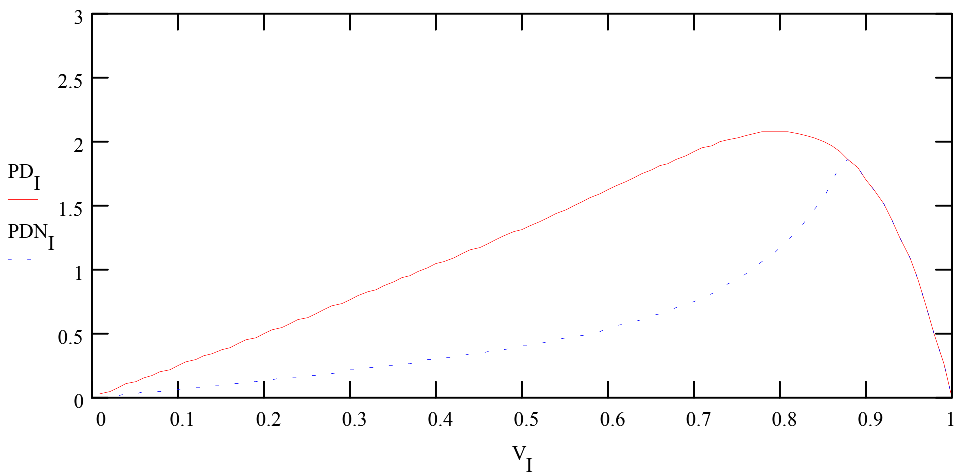


Figure #35 : Graphical Representation of Power Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

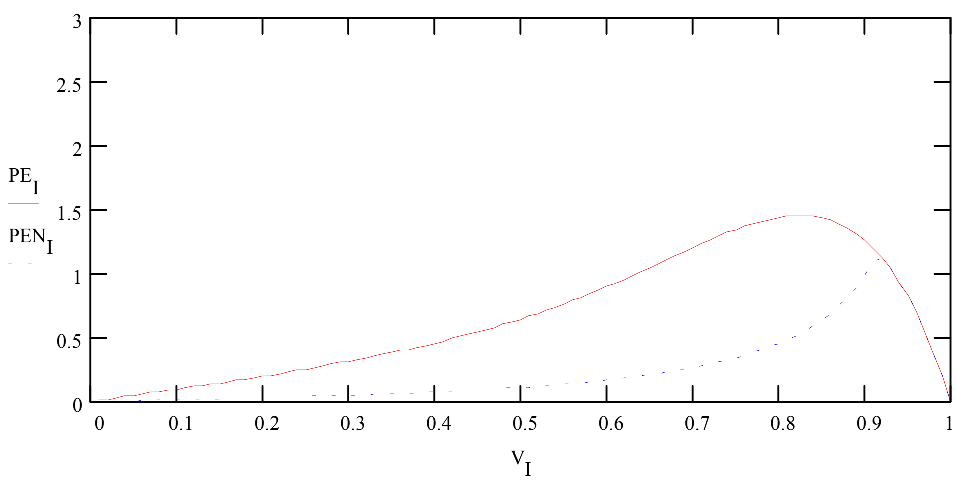


Figure #36 : Graphical Representation of Power Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

VII COMPARISON OF ATL STARTING METHODS VERSES CURRENT LIMIT STARTING METHODS AND THEIR EFFECTS ON REACTIVE POWER, TOTAL POWER, AND POWER FACTOR DURING MOTOR STARTING.-

While torque and power delivered by the motor to the load are of the most importance when determining the ability of a motor under the control of a softstart to accelerate a load, the quantities of total power, reactive power and power factor are of interest. Since we know applied voltage and current drawn, we can calulate the total power. Since we know real power and total power, we can calculate reactive power and power factor. These calculations are shown below and their plots are shown in the following figures.

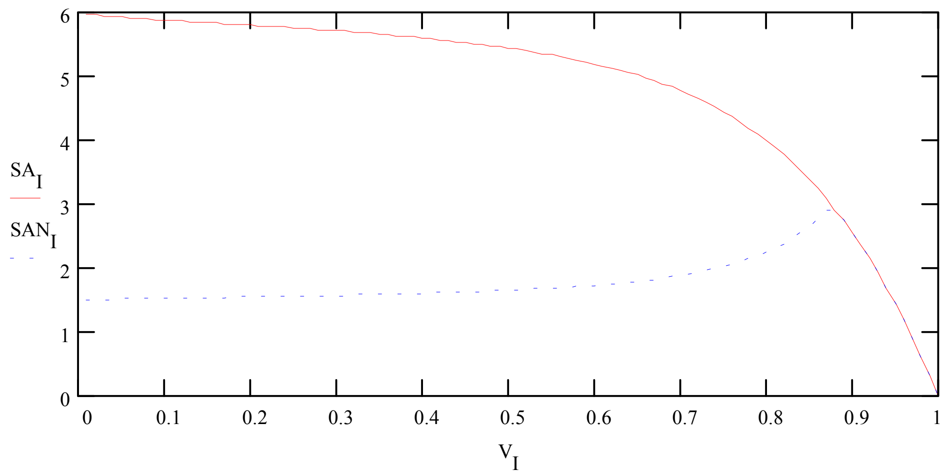


Figure #37 : Graphical Representation of Total Power Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

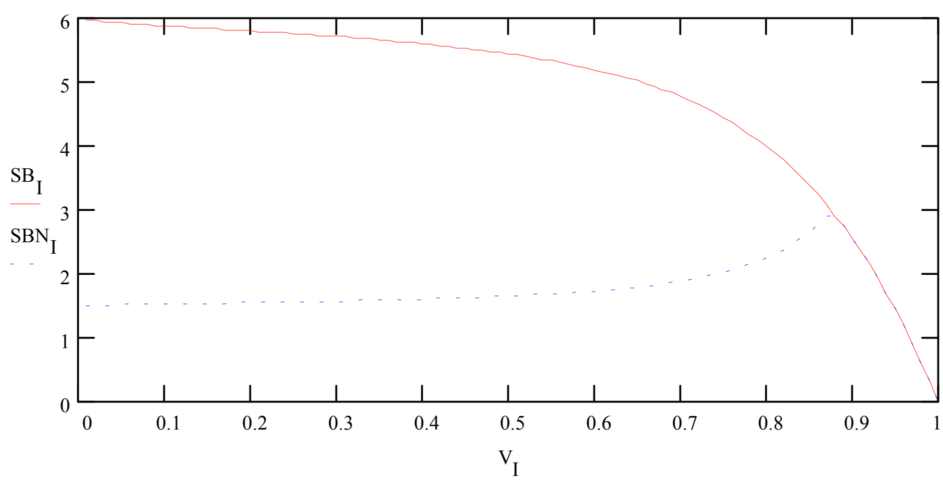


Figure #38 : Graphical Representation of Total Power Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

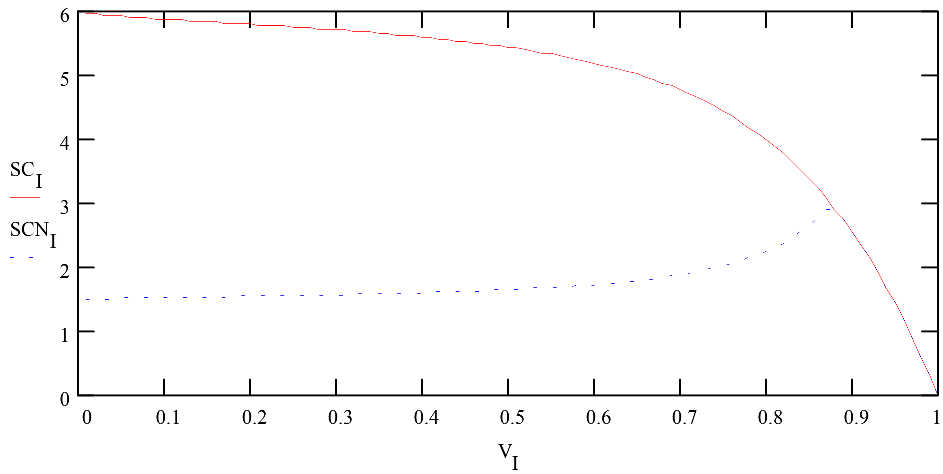


Figure #39 : Graphical Representation of Total Power Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

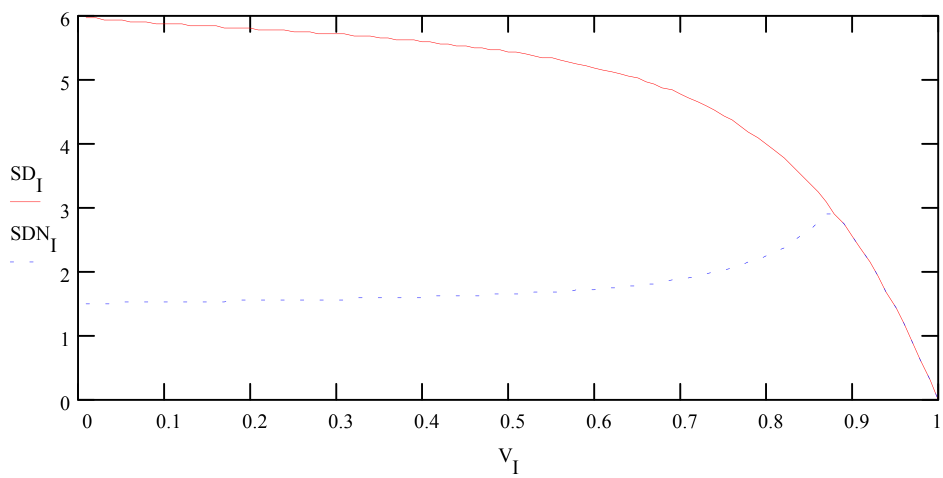


Figure #40 : Graphical Representation of Total Power Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

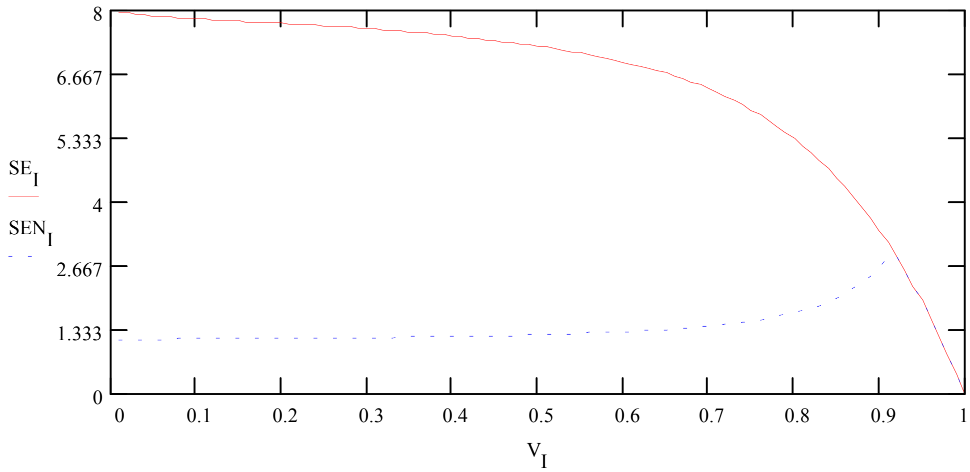


Figure #41 : Graphical Representation of Total Power Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

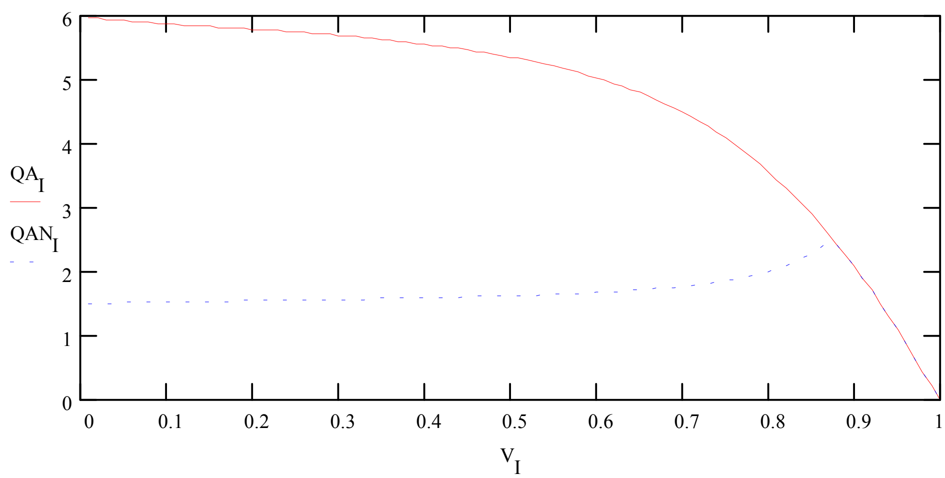


Figure #42 : Graphical Representation of Reactive Power Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

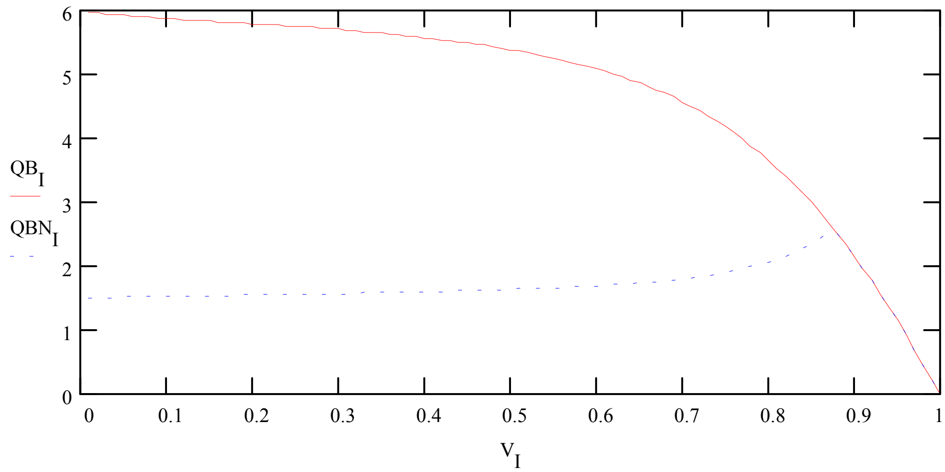


Figure #43 : Graphical Representation of Reactive Power Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

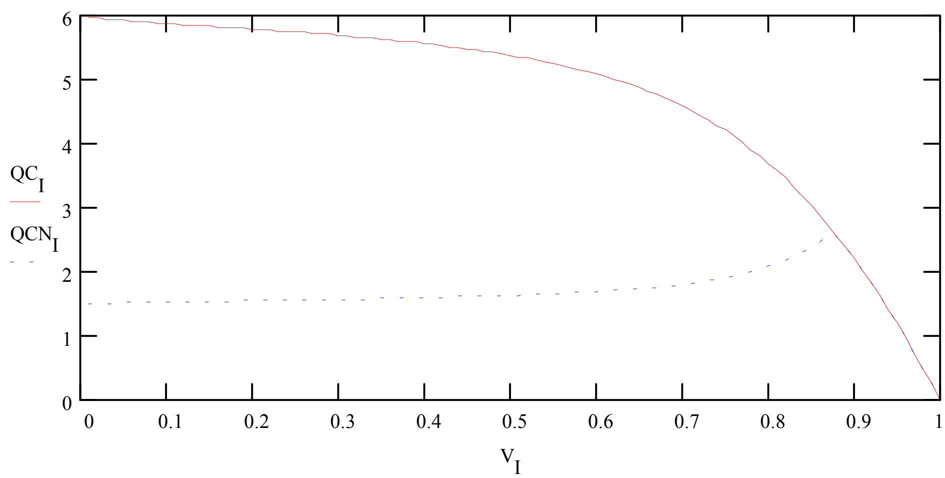


Figure #44 : Graphical Representation of Reactive Power Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

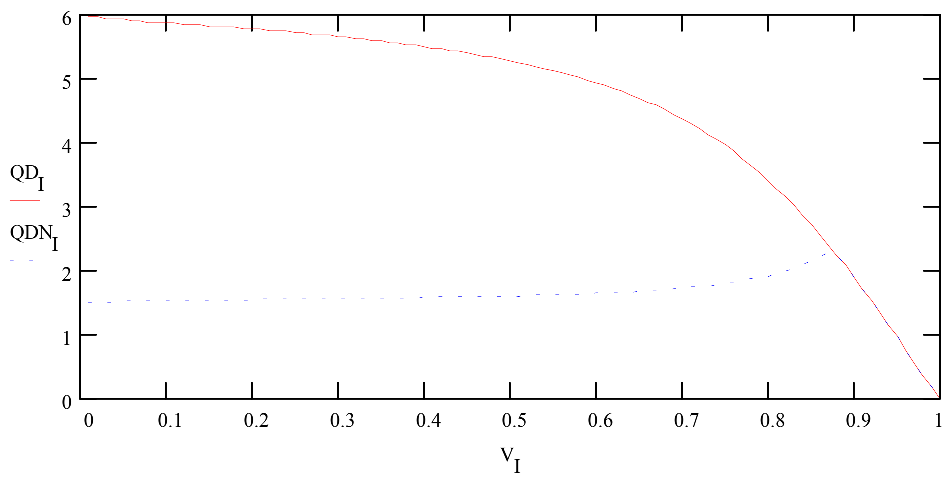


Figure #45 : Graphical Representation of Reactive Power Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

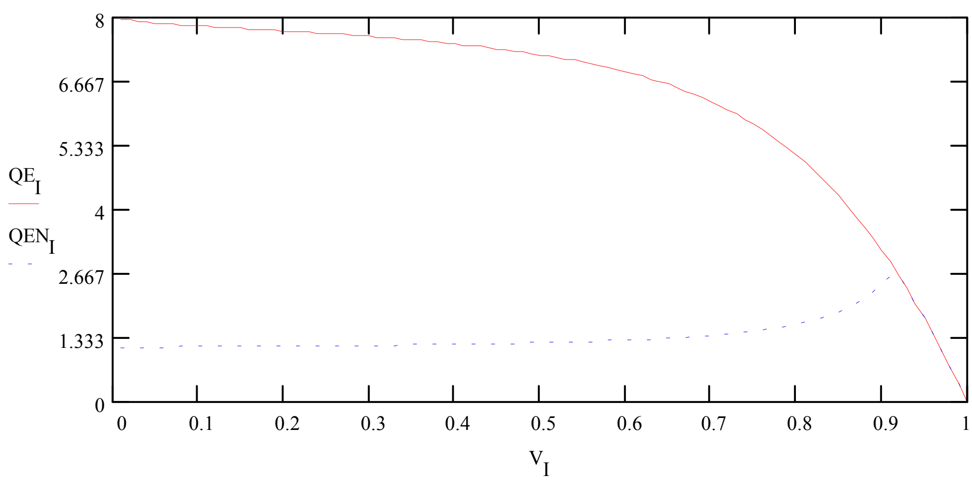


Figure #46 : Graphical Representation of Reactive Power Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

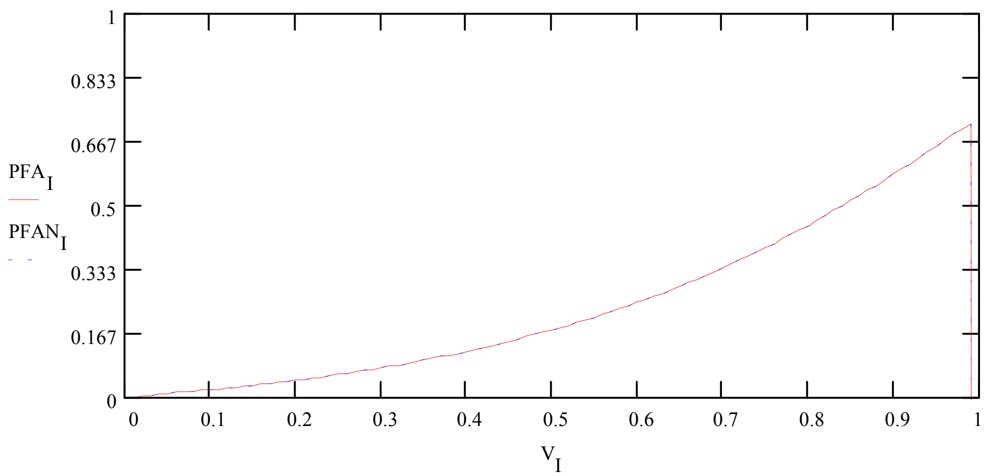


Figure #47 : Graphical Representation of Power Factor Vs. Speed for a NEMA Design A Motor Under Current Limit Starting as Compared to ATL Starting.

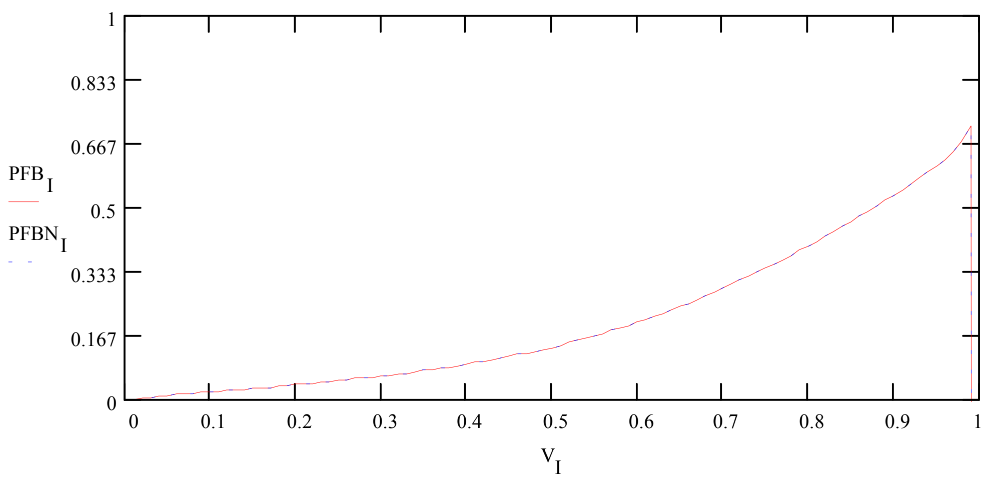


Figure #48 : Graphical Representation of Power Factor Vs. Speed for a NEMA Design B Motor Under Current Limit Starting as Compared to ATL Starting.

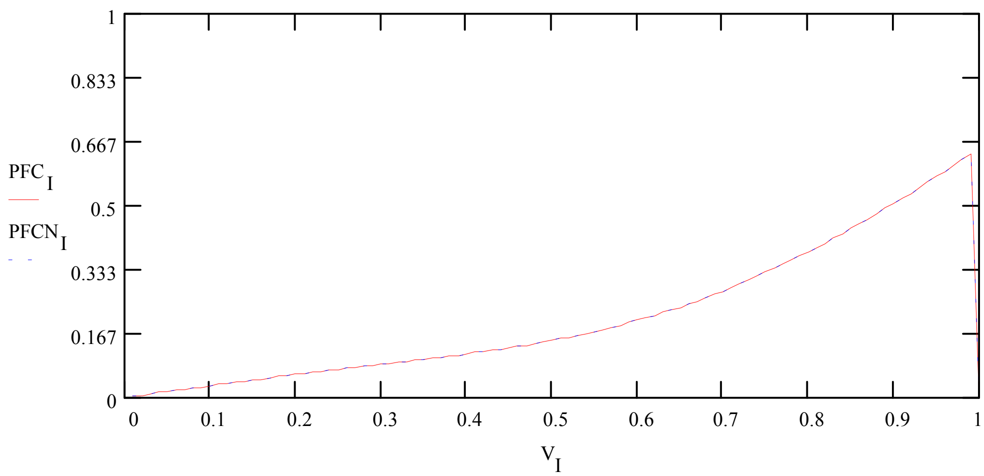


Figure #49 : Graphical Representation of Power Factor Vs. Speed for a NEMA Design C Motor Under Current Limit Starting as Compared to ATL Starting.

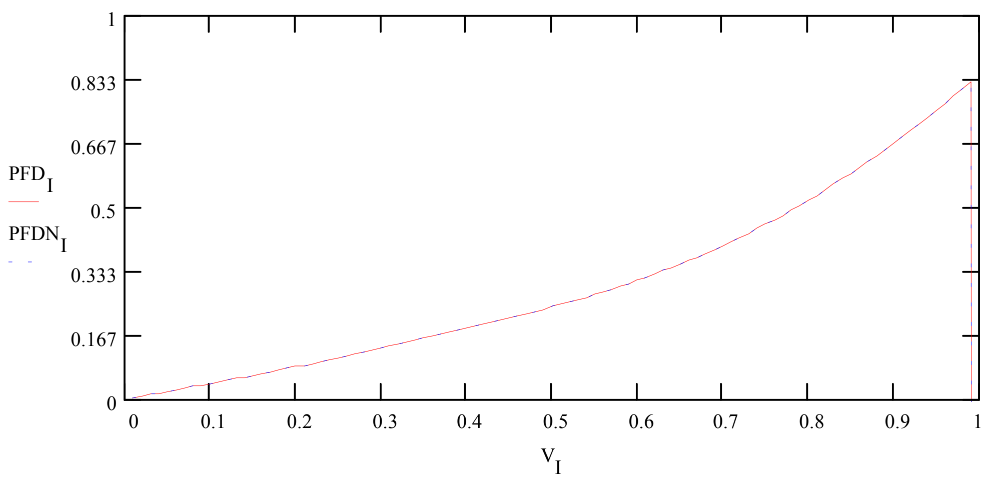


Figure #50 : Graphical Representation of Power Factor Vs. Speed for a NEMA Design D Motor Under Current Limit Starting as Compared to ATL Starting.

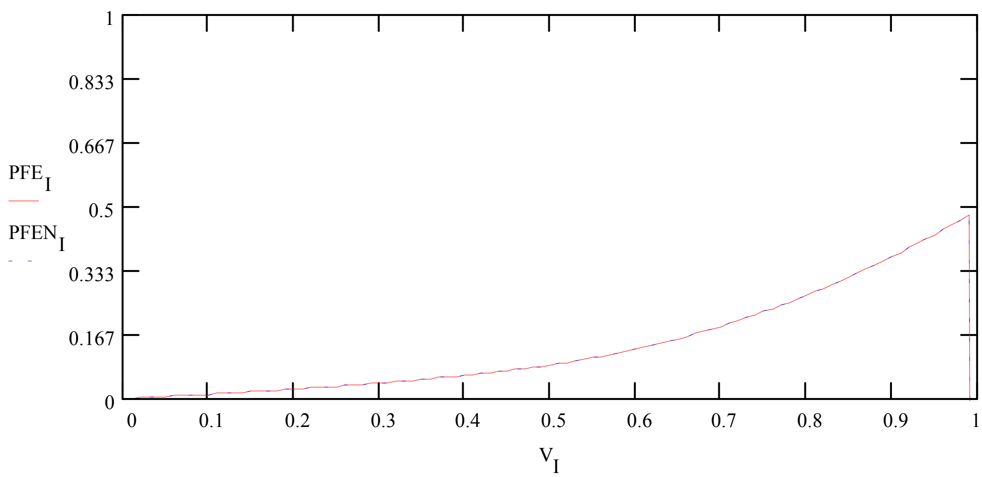


Figure #51 : Graphical Representation of Power Factor Vs. Speed for a NEMA Design E Motor Under Current Limit Starting as Compared to ATL Starting.

VII CONCLUSION -

In this paper, we have shown a method to mathematically model motor ATL starting characteristics using curve fitting techniques. Then, knowing the relationships between current, voltage, power, speed, and torque, we have modified these equations to derive the effect that using a current limiting starting device to start the motor would have on the motor electrical characteristics. Finally, we have displayed a detailed comparison of motor electrical characteristics under both motor starting methods for the various standard NEMA Design motors.

Note: paper modified 02/12/01 to correct math errors.