Design and Modelling of an Automatic 3-Point Starter of a Shunt DC Motor

Ovbiagele Umahon, Jerome, Dada Keshi
Lecturer, Department of Electrical/Electronic Engineering
Auchi Polytechnic, Auchi

Abstract:- The dc motor current is very high at starting when the back emf of the motor is zero. This high initial current can damage the motor if the inrush current is not limited to a safe value. Starters are used to limit the high inrush current. Or a device with a variable resistor which is usually connected in series with the armature windings of the motor so that the starting inrush current can be reduced to a safe value. However, limiting the high inrush current is a problem. This paper discusses control methods for limiting this high starting current to a save value; and a step by step design of an automatic three point simulated in Matlab/Simulink environment.

***Keywords**:- Armature Winding, Back EMF, High Inrush Current, Variable Resistor.*

I. INTRODUCTION

The back emf of the dc motor is zero when the motor is stationary since the back emf is directly proportional to motor speed, i.e. $E_b \alpha N$. Initially, when the motor is about to start, the current of the motor will only be limited by armature resistance in the circuit. The armature resistance is usually of low value and when full load voltage is applied across the motor terminals, the motor will draw heavy current since the armature resistance is inversely proportional to the resistance of the armature circuit.

Equation 1 gives the starting current of the motor

$$I = \frac{V}{R_a} \qquad (1)$$

Where,
V = Source voltage
I_a = Armature current
R_a = Armature resistance

Therefore to limit the starting current to a harmless value, the voltage V value can be reduced or armature circuit resistance R_a value increased. When the motor starts to rotate in the existence of magnetic field, the back Eb is established. As the motor speeds up the back emf grows gradually. Equation 2 gives the motor voltage.

$$V = E_b + I_aR_a. \qquad (2)$$

At starting $E_b = 0$ so equation 2 would be

$$V = IaRa \qquad (3)$$

Where
E_b = back emf

By design the value of armature resistance is usually, small of the order of 0.1Ω to 0.5Ω. And when rated voltage is applied to the motor, then motor draws heavy current from the supply. Such heavy current may cause the following:

- Sparking at commutator
- Damage to armature winding insulation due to overheating.
- Large dip in supply
- High starting torque [6]

In present times, several methods are used by industries for starting of dc motor. These external methods used mainly protect the dc motor [2]

II. THE NEED FOR STARTER FOR DC MOTOR

In order not to damage the motor winding as a result of the high starting current of dc motor, the dc motors need to have starter which can limit the starting current to a save value.

Special control and protection equipment are provided for Dc motor in order for it to function properly. The reasons for providing dc motors with starters are as follows:

- To protect motor against damage of short circuit current
- To protect the motor against damage from long term overloads
- To prevent high starting inrush current
- To provide a convenient manner in which to control the operating speed of the motor [1].

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III. STARTING OF DC MACHINE WITH THREE POINT STARTER

The motor armature will not rotate when the dc motor is about to start, hence the back emf, which is the internal generated voltage, will be zero. The back emf will grow gradually as the speed at the armature increases [6]. The armature current equation is given by equation 4

$$I_a = \frac{V - E_b}{R_a} \quad (4)$$

The back emf of dc motor is given by

$$E_b = \frac{P\phi ZN}{60A} \quad [6] \quad (5)$$

P = Numbers of poles
Φ = flux
N = speed of armature in rpm
Z = Total armature conductors
A = Number of parallel paths in which the Z number of conductors are divided.
and has a major role to play in case of the starting of dc motor.

From the equation 5, the E_b is directly proportional to the speed N of the motor. At starting N = 0, so E_b will be zero, in this state equation 4 is reduces to equation 1. Because there is no back emf heavy current will flows through the armature winding which will be almost ten times greater that its rated current and the motor may get burnt as a result of the I^2R losses in the motor [2]. One of the remedies to the high inrush current is to insert an external resistor in series with the armature. High value resistance will reduce high initial current in the motor.

Three resistances R_1, R_2 and R_3 are connected in series with external circuit in three point starter. The resistances are gradually removed one after the order after a given time interval as the motor generates back emf and the rated current will flow through the armature winding. Under this state, the motor runs on the rated speed [7].

When the external resistance is not added to the armature circuit the motor may have winding failure or it may experience heavy torque.

$$T \propto \emptyset I_a \quad (6)$$

From equation 6, torque is directly proportional to the current.
Where
T = Torque
Φ = motor flux
By use of starter

$$V_a = E_b + I_aR_a + I_aR_{ext} \quad (7)$$
$$V_t = E_b + I_a(R_a + R_{ext}) \quad (7b)$$

When the back emf is zero in equation 7, we have

$$I_a = \frac{V}{R_a + R_{ext}} \quad (8)$$

Where
R_{ext} = external resistance
High value of the external resistance can reduce the armature current to a safe value.

IV. THE DESIGN OF AN AUTOMATIC THREE POINT STARTER OF DC MOTOR

A. The Parts of DC Motor Starter

The different types of starters used in industries and their principle of operation have been treated by various electrical engineering textbooks, such as the three point starter and 4 pointer starter. In this work, we shall limit our study to the design of three point starter.

The starting resistance comprise three resistors which are removed in steps as the dc motor attains speed. Starter design is made of two parts:

- To determine the number and value of the resistors that is required to reduce the initial high current to allowable value.
- To design a current circuit that can bypass the starting resistor in steps and at appropriate time [7].

B. Design Calculation of DC Motor Starter

The design parameters are as follows:
Power = 10HP,
Armature voltage = 240V
Armature current = 21.18A
Armature resistance = 2.581ohms.
Motor speed 1750rpm

The motor is to limit its starting current to 2 times the rated current value and the resistors will be removed when the motor reached its normal speed.

In this design, we shall determine the following:

- The number of steps of starting resistance needed to limit the current to the stated value
- The value of every segment of the resistor
- The voltage each stage of the starting resistance will be cutout

In this design, the starting resistors will be removed in three steps. The rated current of the motor is 21.18A. The starter will limit the starting current to 2 times the rated current. The current is reduced to rated value when armature generates internal voltage Eb as the speed of the motor increases. The first resistor is removed when the rated current value is reached. When the first resistor is removed the current will rise again however each value of each segment resistor are selected so that current can only rise to two time the rated value of current. Each time the motor gains more speed, the back emf will also increase and the armature current will decrease to rated value. When this happens the second resistor is removed and this will cause the starting current to increase two times the rate current again. The 3rd segment of resistor is removed following the same procedure.

The terms used in the design are defined as follow:
E_b = Back emf
V = Terminal voltage
I_a = Irated
I_{max} = Maximum current
R_a = armature resistance
$R_{total} = R_1 + R_2 + R_3$ = total external resistors

In this design the peak ratio (PR) is unequal.

The voltage equation at the armature side is:

$$V_a = E_b + I_a R_a \quad (9)$$

The required maximum armature current is 2 times rated current. The peak value for each closure, (peak ratio, PR) is set not equal to each other [4].

$$I_{max} = 2 \text{ x } I_{rated} \text{ [3].}$$
$$= 2 \text{ x } 21.18$$
$$= 42.36\text{A}$$

At the starting point the motor is at rest, $E_b = 0$

$$V_a = 0 + PR_0 I_a (R_T + R_a) \quad (10)$$
$$240 = 2 \text{ x } 21.18 (R_T + 2.581)$$
$$240 = 42.36 R_T + 109.33$$
$$R_T = \frac{240 - 109.33}{42.36}$$
$$= 3.085\Omega$$

Where $R_T = R_1 + R_2 + R_3$

A moment later, the current begins to fall to the valley value, and at the same time the back emf, E_b begins to rise

$$E_{b1} = Va - I_{rated} \text{ x } (R_T + Ra) \quad (11)$$
$$E_{b1} = 240 - 21.18 \text{ x } (3.085 + 2.581)$$
$$= 120\text{V}$$

Closure of R_1 occurs and the current value climbs to the top value and by setting of $PR_1 = 1.6$

$$R_2 + R_3 = \frac{V_a - E_{b1}}{PR_1 \text{ x } I_{rated}} - R_a \quad (12)$$
$$= \frac{240 - 120}{1.6 \text{ x } 21.18} - 2.581 = 0.960\Omega$$

The current begins to fall to the valley value, and at the same time the back emf, Eb begins to rise.

$$E_{b2} = V_a - I_{rated} \text{ x } (R_2 + R_3 + R_a) \quad (13)$$
$$E_{b2} = 240 - 21.18 \text{ x } (0.960\Omega + 2.581)$$
$$E_{b2} = 165 \text{ V}$$

Closure of resistor R_2 occurs and the current value rises to the top value and by setting $PR_2 = 1.2$

$$R_3 = \frac{V_a - E_{b2}}{PR_2 \text{ x } I_{rated}} - R_a \quad (14)$$
$$R_3 = \frac{240 - 165}{1.2 \text{ x } 21.18} - 2.581$$
$$R_3 = 0.370$$
$$E_{b3} = Va - I_{rated} \text{ x } (R3 + Ra) \quad (15)$$
$$E_{b3} = 240 - 21.18 \text{ x } (0.37 + 2.581)$$
$$E_b = 178\text{V}$$

Closure of resistor R_3 occurs and the entire external resistors are removed from the circuit.

PR0,1,2	Imax (A)	Eb (V)
2	42.36	120
1.6	33.89	165
1.2	25.42	178

Table 1:- The Value of IMAX and Eb

R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
2.125	0.590	0.370

Table 2:- Calculated External Resistance.

The resistor R_1 with value 2.125Ω is cut out when the back emf is 120V, the resistor R_2 with value 0.59Ω is cut out when the back emf is 165V and the resistor R_3 is cut out when the back emf is 178V.

V. SIMULATION

In this paper, a model of automatic three point starter is developed in Matlab/simulink environment by the authors to explain the concept of three point starter. In this model the breakers are synchronized in a way that each resistor out of the three is progressively removed one after the other [5]. Each breaker is shunt with the specific resistance; these are arranged in series with the armature winding. At start breaker1is in off or '0' position which is step with particular time interval to close or'1' position and resistance R_1 is by-passed by the short circuit. R_1 is removed from the external resistance. Similarly, R_2 and R_3 by breakers 2 and 3 are also removed at particular time interval with each other. The whole resistances are cut off in three steps.

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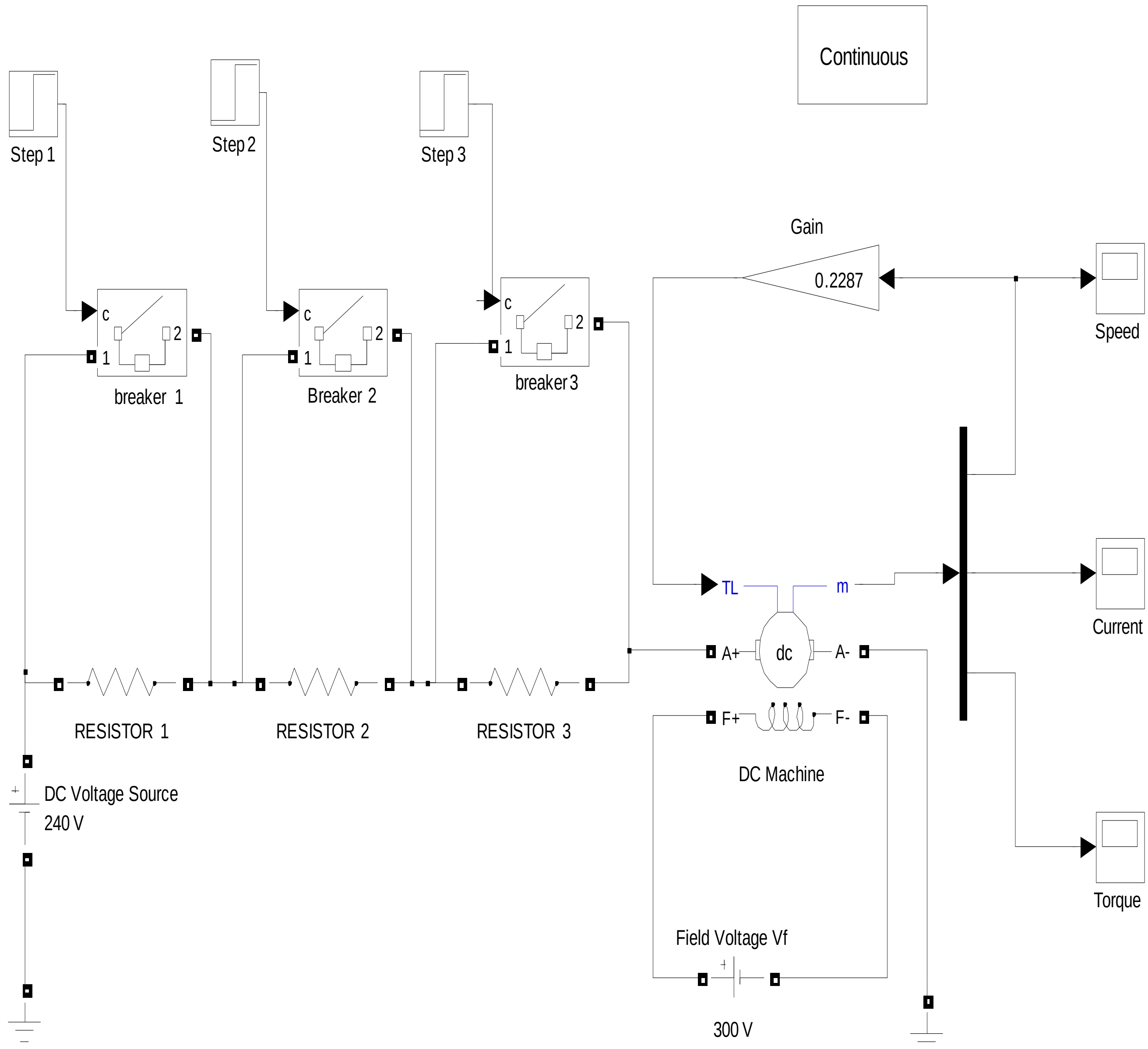

Fig 1:- Developed Matlab/Simulink DC Motor Starter System

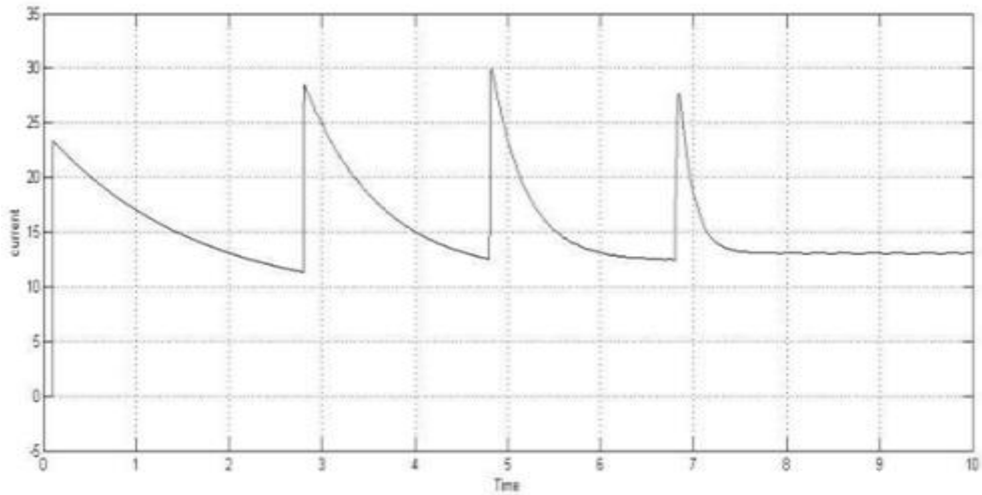

Fig 2:- Current vs Time

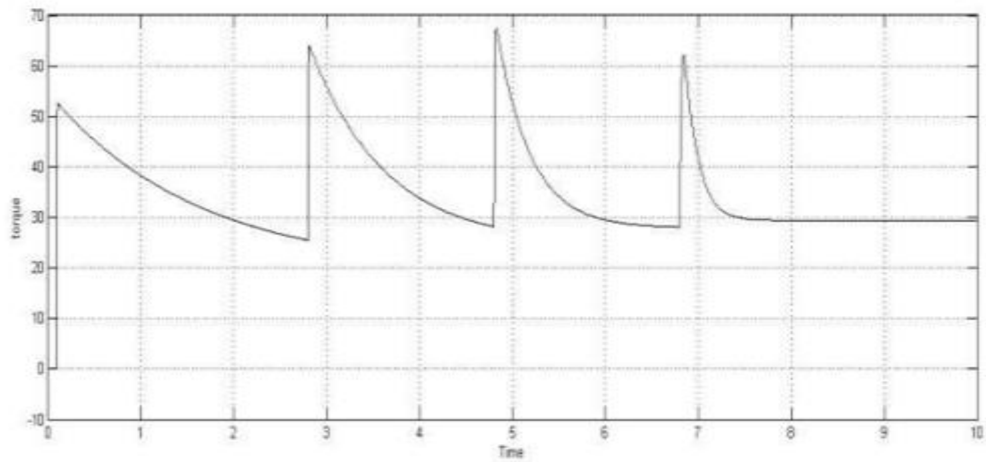

Fig 3:- Torque vs Time

From the current vs time graph, the starting current has been limited. One of the three resistors is removed when the currents shoot back once the armature current reaches the rated current. The three maximum points in the graph show that three resistors were removed.

VI. CONCLUSION

In this paper, the authors have designed an automatic three point starter in which resistances are cut-off after particular interval of time one by one from the circuit automatically. This method can provide 50% of the E_b value at the starting point for maximum load but not for full load. This is because the input voltage is fixed at 240V and does not have the flexibility to reduce resistance. Voltage control will be more efficient if a lower starting voltage can be fed to the motor and then armature voltage can be increased consistently by the controller.

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