

Simulation and analysis of the possibilities of traction electric motor

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ABSTRACT

Great efforts are directed towards the use of electrical vehicles in transportation. Mathematical modeling tools can provide a powerful approach for investigating electrical vehicles and are successfully implemented by applying Matlab/Simulink. In this paper, the mathematical simulation model of Series Excited DC motor (tractive motor) on Matlab/Simulink was implemented and investigated. The main objective of this study is to assess the use of Series Excited DC motor (tractive motor) for the new Amman city express bus project and evaluation of its performance characteristics in different running and loading cases. All simulation results are plotted and discussed. Simulation results showed that Series tractive DC Motor is very suitable in electric (Buses) transport devices. The starting current was about 460 A, (8 times more than the rated motor current) and 357 A in steady state condition with different loads (passengers). This study confirms the feasibility for the use of the series excited DC motor (tractive motor) in electric buses as alternatives for sustainable and environmentally friendly transportation system.

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1. INTRODUCTION

Public transportation nowadays is one of the most encountered daily problems in most cities of the world. Due to many factors including world fuel crises, environmental concerns, there was a demand for fuel economy and environment friendly transportation vehicles [1]. Electric Vehicles (EV) and Electric Transport Systems (ETS) had acquired great attention and are predicted to be the most used mode of transportation in the near future, due to their advantages as compared to ordinary transportation vehicles [2]. These vehicles are economic with low running costs and maintenance, have better performance capabilities as compared to conventional internal combustion engine vehicles. Since these vehicles use no fuel, they are predicted to reduce harmful carbon emissions by 25-60% and thus reducing pollution and greenhouse gases. Moreover, the use of renewable energy for charging is an important option that helps in reducing fuel problems. In comparison with an internal combustion engine, electric motor has high efficiency and lower energy losses. The efficiency of the electric motor is about 90% against 25% of an internal combustion engine. Researchers are continuously working on ETS and EV to improve their range, performance and reliability [3]. In this field, the ongoing research efforts are focused on increasing the life time of the battery bank [4] that provides the advantages of low power rated converter and better load profile for the battery bank. Clegg (1996) [5] indicated that the energy efficiency can be amplified by using regenerative braking of motors (tractive motor) [6]. His results indicated a good dynamic performance and robust stability with more recovered energy. Accordingly, regenerative braking appears to be suitable for hybrid electric vehicles and for fuel cell electric vehicles as well [7].

Recently, in the Capital city of Jordan, Amman, a two lane Express Bus Project of 25 km long has been lunched [8]. The express bus project, in its current form Figure 1 employs the use of fossil energy sources (Diesel).



Figure 1. A view of Amman Express Bus Project

However, the current investigation suggests the use of electric buses and the better investment of the French funding [9] in establishing the electrical network required for this project. Moreover, the study also suggests the use of traction electric motors instead of internal combustion engine motors that requires fossile fuel (diesel), taking into consideration the geographical nature of Amman and the possibility of employing solar energy to generate the electricity required for running these electric buses.

The main requirements of a traction electric motor are:

- a) The ability to realize the maximum torque for the entire speed range.
- b) The ability to work in two directions without any additional devices.
- c) The simplicity of the air cooling design.
- d) The ability to operate in the generator mode.

Electric vehicles use several electric motors to drive individual wheels in order to increases the traction power of the vehicle. A series excited DC electric motors are used as traction motors [10].

2. THE MATHEMATICAL MODEL

Computer modeling has always been used for industrial designs, especially for EVs which have benefited greatly from the accelerated use of simulation programs in evaluating all vehicles aspects, including energy consumption. During the current study, a mathematical model of a direct current electric (DC) motor with series excitation - traction electric motor - for dynamic modes, Figure 2 was established.

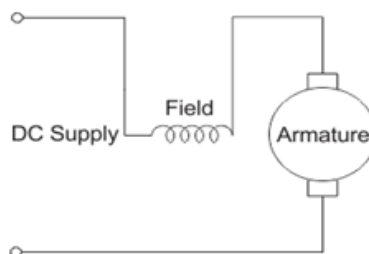


Figure 2. A schematic diagram of a direct current electric motor with series excitation

The implementation of the second Kirchhoffs' law and the basic equation of motion give the possibility of obtaining the mathematical model for a DC Motor [11].

$$i_a R_{tot} + L_{tot} \frac{di_a}{dt} + E_a = V_t \quad (1)$$

Where; $E_a = K\phi\omega$ is the internal induced voltage of the armature. The total resistance of the motor (R_{tot}) could be calculated from the equation:

$$R_{tot} = R_{arm} + R_{series} + R_{interpoles}$$

The total inductance of the motor (L_{tot}) can be easily calculated from the equation:

$$L_{tot} = L_{arm} + L_{series} + L_{interpoles}$$

Substituting the expression of the internal induced voltage of the motor into the second Kirchhoff law, gives:

$$i_a R_{tot} + L_{tot} \frac{di_a}{dt} + K\phi\omega = V_t \quad (2)$$

Then, supplementing the mathematical model of the DC motor with the basic equation of motion of the electric drive can be illustrated with the following equations:

$$T - T_L = J \frac{d\omega}{dt} \quad (3)$$

$$T = K\phi i_a \quad (4)$$

The substituting of expression (4) into equation (3) gives a detailed equation of motion of the electric drive.

$$K\phi i_a - T_L = J \frac{d\omega}{dt} \quad (5)$$

Then, rewrite equations (1) and (4) to form

$$\frac{di_a}{dt} = \frac{1}{L_{tot}} (V_t - i_a R_{tot} - K\phi\omega) \quad (6)$$

$$\frac{d\omega}{dt} = \frac{1}{J} (K\phi i_a - T_L) \quad (7)$$

As a result of such transformations, a nonlinear mathematical model of the direct current electric motor with series excitation was obtained. The non-linearity of the model is related to the nonlinear characteristics of the machine's magnetic circuit, which could be attributed to the nonlinear relationship between the flux of the machine and the field current. The obtained equations in the employed model are differential equations of the first order. To solve the last two equations, Euler's method [12] was employed. Thus, equations (6) and (7) were written as the algebraic equations (8 & 9), and were then easily implemented with the computer application.

$$\frac{\Delta i_a}{\Delta t} = \frac{1}{L_{at}} (V_t - i_a R_{tot} - K\phi\omega) \quad (8)$$

$$\frac{\Delta \omega}{\Delta t} = \frac{1}{J} (K\phi i_a - T_L) \quad (9)$$

The algorithm for the solution was:

$$\Delta i_{am} = \frac{\Delta t}{L_{at}} (V_m - i_{am-1} R_{tot} - K\phi\omega_{m-1}) \quad (10)$$

Where Δi_{am} is the increment of the armature current at “ m ” step of integration; “ m ” is the step of integration; V_m is the voltage at “ m ” step of integration applied to the armature circuit; Δt – is the integration step; i_{am-1} is the value of the armature current at “ $m-1$ ” which refers to the previous step of integration; ω_{m-1} is the value of the angular velocity of the DC series motor on “ $m-1$ ” step of integration;

$$i_{am} = i_{am-1} + \Delta i_{am} \quad (11)$$

Where i_{am} is the increment of the armature current at “ m ” integration step.

$$\Delta \omega_m = \frac{\Delta t}{J} (K \phi_{am} - T_{Lm}) \quad (12)$$

Where $\Delta \omega_m$ is the increment of the angular velocity at the “ m ” integration step and T_{Lm} is the value of the load moment of the drive at the “ m ” integration step.

$$\omega_m = \omega_{m-1} + \Delta \omega_m \quad (13)$$

Equations (10) and (12) were used for the determination of the increments in the current Δi_{am} and the velocity $\Delta \omega_m$. Equations (11) and (13) on the other hand, were used to calculate the current i_{am} and the velocity ω_m .

3. SIMULATION RESULTS AND ANALYSIS

In the current investigation, two simulation models were employed and their results were evaluated. These included Excel and Matlab/Simulink [13] models. The main similarity between these methods of simulation (Excel and Matlab/Simulink) is basically the mathematical model [14]. Excel helps in investigating the statistical and dynamic modes of energy [15, 16]. Briefly, for simulating an electric DC motor with series excitation in a dynamic mode [17], values of the independent variable (t) are introduced to column 1 of the Excel sheet, starting with the value $t = 0$.

The value of the integration step - the increment - (Δt) is determined using the empirical formula:

$$\Delta t \leq \frac{\tau_{\min}}{5} \quad (14)$$

The minimal time constant (τ_{\min}) is determined by comparing the values $\tau_M = \frac{J R_{tot}}{C^2}$, and $\tau_a = \frac{L_{tot}}{R_{at}}$.

Values of i_a , obtained from equation (11), are introduced to second column (B). Values of (ω_m) as calculated from equation (13) are then introduced to the third column (C) of the spreadsheet. The fourth and fifth columns contained the calculated values of Δi_{am} and $\Delta \omega_m$ obtained from equations (10) and (12), respectively. Excel results are better than Matlab/Simulink for investigating the statistical modes of energy.

All calculations using the software package “Matlab” are made with variables, as with matrices [18]. The transient process time (t) from 0 to the end of the transient process $T_{tp} = 5\tau_{\min}$ is given in the form of a matrix $t = [0 : \Delta t : T_{tp}]$, where,

$$\Delta t = \frac{\tau_{\min}}{10} \quad (15)$$

Performing the process of modeling of the transient process for an electrical circuit with an induction coil when turned on to a DC voltage, is demonstrated by the following example. The used mathematical model in this example is a classical solution for a linear inhomogeneous differential equation of the first order. The parameters of the electrical circuit:

$L = 1; V = 20; R = 10; \tau_{arm} = L / R; \text{delta} = \tau_{arm} / 10; T_{pp} = 5\tau_{arm}; t = [0 : \text{delta} : T_{pp}]; i = \frac{V}{R(1 - \exp(-t / \tau_{arm}))};$
 $\text{plot}(t, i).$

Figure 3 shows the dependence of the current in the electrical circuit with an inductance coil, when switched to a constant voltage in the transient process.

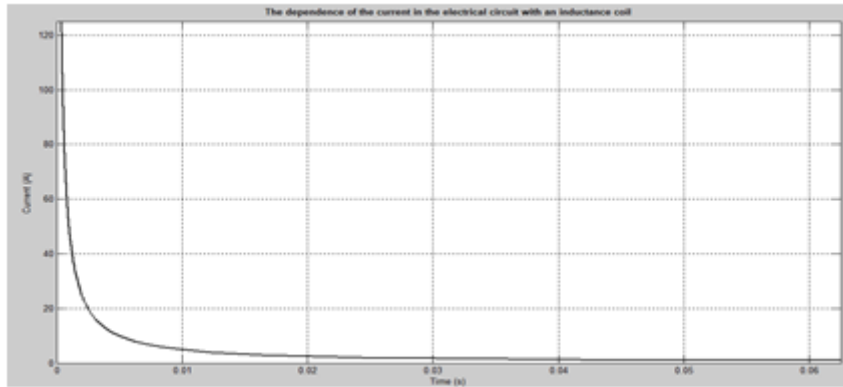


Figure 3. The dependence of the current in an electric circuit with an inductance coil

The most effective tool for mathematical modeling of electro technical objects in dynamic modes is the Matlab/Simulink [10]. Figure 4 represents a structural scheme of the mathematical model of an electric DC motor with series excitation based on equations (5) and (6).

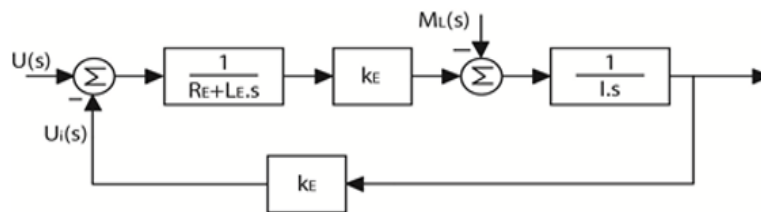


Figure 4. The mathematical model of an electric DC motor with series excitation in the form of a structural scheme.

Analysis of the scheme revealed a nonlinear model. The model contains three non-linear links, using which the motor torque (T) and the motor back EMF were determined [19]. The model of series excited DC motor with a direct and soft-linear rising voltage-startup in the program of Matlab/Simulink is shown in Figure 5, the Matlab/Simulink Model blocks description is listed in Table 2. The motor parameters used in the current simulation study are listed in Table 1 at: A) no-load, B) 50% rated load and C) rated load. The employed Matlab/Simulink blocks description is listed in Table 2.

Table1. Motor Parameters

Quantity	Symbol	
Armature Resistance	R _a	0.05 Ω
Electromechanical Time Constant	T _a	0.1 c
Moment of Inertia	J	10Kg – m ²
Load Torque	T _l	200 Nm
Armature (Supply) Voltage	V _a	220 V

Table 2. Matlab/Simulink Model blocks description

Scope	Display signals- Current, Torque and Speed- generated during simulation
Gain	Multiply input by constant
Math Function	Perform mathematical function
Product	Multiply and divide scalars and nonscalars or multiply and invert matrices
Sum	Add or subtract inputs
Constant	Generate constant value
Step	Generate step function as input voltage and load
Ramp	Generate constantly increasing input voltage
Transfer Function	Model linear system by transfer function for motor circuit
Saturation	Limit input signal to the upper and lower saturation values of input voltage
Selector	Select input elements from multidimensional signal to display

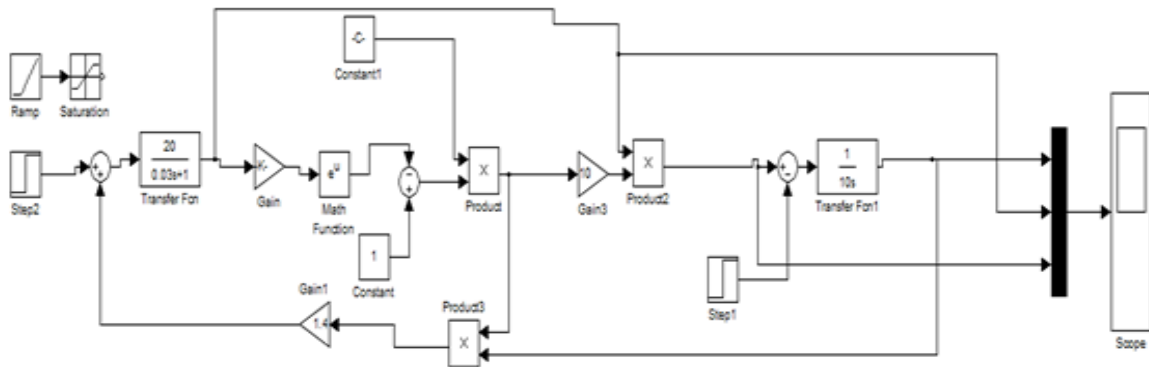


Figure 5. Matlab/Simulink mathematical model of electric DC motor with series excitation

Figure 6 shows the dependence of the angular velocity, armature current and the moment of electric DC motor with series excitation during a direct start-up obtained by the simulation in the Matlab/Simulink program. Figure 7 shows the dependence of the angular velocity, armature current and the moment of electric DC motor with series excitation during a direct start-up, obtained by simulation in the Matlab/Simulink program.

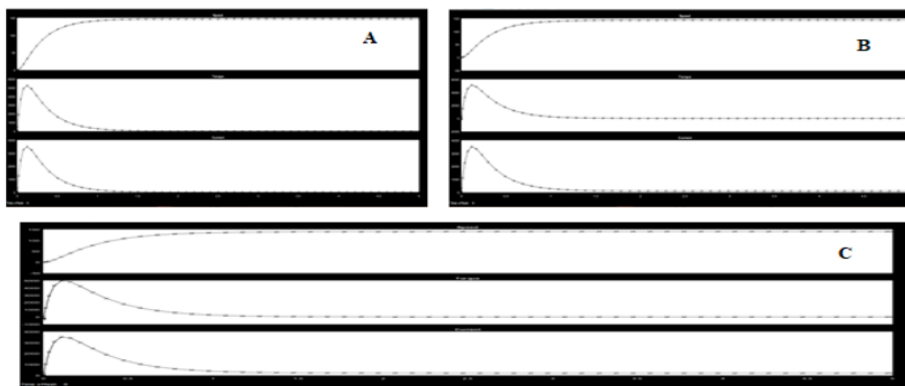


Figure 6. The direct start-up dependence of the angular velocity, the armature current and the moment of electric DC motor with series excitation at **A**: at no-load; **B**: at 50% of rated load and **C**: at rated load

As could be concluded from figures 5 and 6, the simulation results revealed that the starting current of the motor was 460 A, but after a transient condition period, the current reached a value of 357 A and became stable. Similarly, at starting conditions, the motor torque reached a value of 645 N.m but after 12 s, the motor torque was stabilized to a value of 500 N.m [6]. The figures also indicated that the speed was changing smoothly (0-145) rad/s and was stable. The above mentioned values of current, torque and speed are for the smooth starting method [10].

The energy efficiency and the minimizing of the electric energy consumption in the ETS can be amplified by using regenerative braking. Depending on the nature of the roads, there is a good possibility for the utilization of regenerative braking with good dynamic performance, more recovered energy and with a chance of choosing a better control algorithm for the vehicle controller [20]. When driving on a flat road surface at a constant speed, the consumption of electric energy is the smallest. An increase in the device weight, road resistance and resistances while driving up or down the hill will decrease or increase the ability of acceleration and thus increasing or decreasing the energy consumption during the acceleration or deceleration. However, more energy is recovered during engine braking. Most energy is consumed during the acceleration of the electric transport device [21, 22].

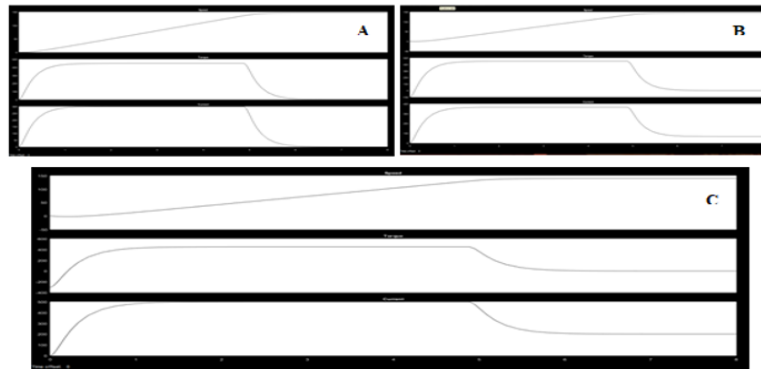


Figure 7. The start-up with a linear rising voltage (pulse-width modulation) dependence of the angular velocity, armature current and the moment of electric DC motor with series excitation: **A:** at no-load; **B:** at 50% of rated load and **C:** at rated load

The effect of sudden changes in motor load, road resistance, passengers load or road slope were also investigated, as shown in Figure 8. Results revealed that the speed, torque and current were not very sensitive to such changes indicating that the motor performance and stability were very good. The results of the current simulation study indicated that the series DC motor reached a steady state speed after a transient condition period not exceeding 1.5 – 2 s and in different loading cases of the electric transport device. The findings of the current study confirms that the Series DC Motor is covering the electric transport requirements with best dynamic performance and is suitable to be used in electric transport devices and generally for electric traction.

Figure (8) shows the dependence of the angular velocity, armature current and the moment of electric DC motor with series excitation during direct start-up and steady state conditions, obtained by simulation in the Matlab/Simulink program when the load of motor was changed during motor running, due to the road resistance and resistances while driving up or down the hill.

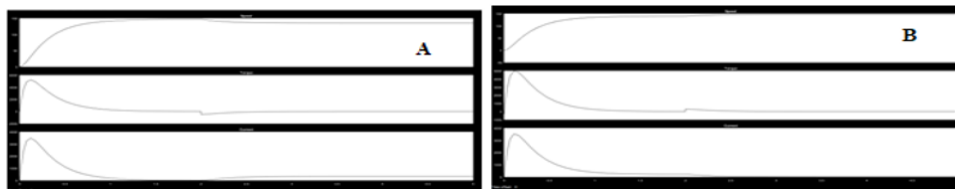


Figure 8. The direct start-up dependence of the angular velocity, the armature current and the moment of electric DC motor with series excitation when the load changing during motor running **A:** with load increasing (up the hill) and **B:** with load decreasing (down the hill)

4. CONCLUSION

The obtained characteristics by Simulink/Matlab of the investigated Series DC motor in terms of speed, current and torque are compatible with the findings of other researchers [23]. In the current work, a Matlab/Simulink mathematical model derivation for the described motor has been carefully described and

discussed taking into consideration the nonlinear relationship between the field current and the machine flux. Simulation results obtained in the current study confirmed the feasibility of the use of the series excited DC motor (traction motor) in electric buses in transportation system as alternatives for internal combustion engine motors. The obtained characteristics for speed, current and torque indicated that the studied motor reached a steady state speed after 6 s at different loads. This result clearly revealed that Series tractive DC motor is very suitable in electric buses transport devices. The starting current was about 460 A, is 8 times more than the rated current of the motor and 357 A in steady state condition with different loads (passengers). In general the Series DC Motor is covering the electric transport requirements and gives the best dynamic performance.

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