Modeling of a Hybrid Vehicle Engine Starting System

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Abstract

The paper deals with a study of the modeling and simulation of a hybrid vehicle prototype starting system comprise of electric and pneumatic motors concepts. The electric starting system is powered by a DC permanent magnet motor, while the pneumatic starting system is powered by a pneumatic motor. The study is extended to include a detailed comparison between the two concepts, and a detailed explanation of the design and implementation of the Electronic Control Unit (ECU) for the engine starting management. MATLAB / SIMULINK-SIMCAP R2013a are tools environments have been utilized for modeling and simulating the components of electric and pneumatic starting systems including; battery, DC motor, pressurized tank, direction control valve, pneumatic motor, and the load produced during engine cranking. The performance of the proposed starting systems is analyzed and investigated. This technique is effective for reliable start and increased service life of both battery and starter motor, and also for the safety of vehicles and passengers. Further, the pneumatic system has other uses in tractors and commercial vehicles (i.e., Lorries, tractors, and buses) such as opening/closing the doors and/or braking system (the infrastructure is already in the place). So, there is no need to build another system.

***Keywords* – Pneumatic Starting; Electric Starting; Automotive Engine Starting System; MATLAB / SIMULINK-SIMCAP R2013a tools.**

1. Introduction

The internal combustion engine cannot self-start, so the initial phase in the operation of an automotive IC engine is the engine starting process. The starting system act as a prime mover for the engine until the ignition begins. This occurred when the crankshaft rotates around 100 to 200 rpm with suitable brake torque, which depends on the compression ratio, number of cylinders, and starting time [1].

Engine starting system converts the stored energy (electrical, hydraulic, mechanical or compressed air) into mechanical rotating energy through a starting motor, which transmits the rotating energy to the engine flywheel. Once it gets the ignition speed, it will automatically ignite, fire, run up to self-sustained speed, and the starting system shuts-off.

The types of IC engine starting systems are; electric hydraulic, mechanical (spring starter) and compressed air systems. The most commonly used for automotive engines is the electric starting system. The problems of the current electric starting system may be summarized as follow:

- The vehicle depends only on one starting system leading to a traffic delay due to the engine un-running in case of the failed starting system.
- The starting system has a limited number of starting cycles; then the battery becomes dead.

- The unnecessary idling causes a decrease in the lifetime of both the battery and the electric starting motor and may need to replace them within a short time. The vehicle idling has local and national impacts as additional costs due to wasted fuel and production of harmful emissions. Unnecessary idling in the USA wastes approximately six billion gallons of fuel annually, costing the country around $21 billion [2].

The starter motors convert electrical energy through a battery into mechanical rotating energy. They work under heavy load and produce big power in a short time and in a small volume. They convey its rotating energy with a pinion to the flywheel. For initiating an internal combustion engine, the rotating moment of starter motors should be requested being greater. The starter motor must be rotating the engine flywheel at least a minimum starting speed. Also, it must continue to support rotation during initial combustion to maintain momentum until the engine can sustain the operation. The starter motor turns for less than 3 seconds during each starting attempt [3]. In each attempt, the starter motor pinion bounces out and meshes with the flywheel attached to the engine crankshaft. During the compression cycle of each cylinder, the starter motor torque is high, resulting in a higher force on the starter gear teeth. Because of the lack of overcurrent protection, the traditional starter control through solenoid easily causes short circuits and bums out the starter. So the starter motor and its components are subjected to either mechanical faults like wear, fractures of moving parts or electrical faults like short interrupted circuit and contact resistance increase, etc.

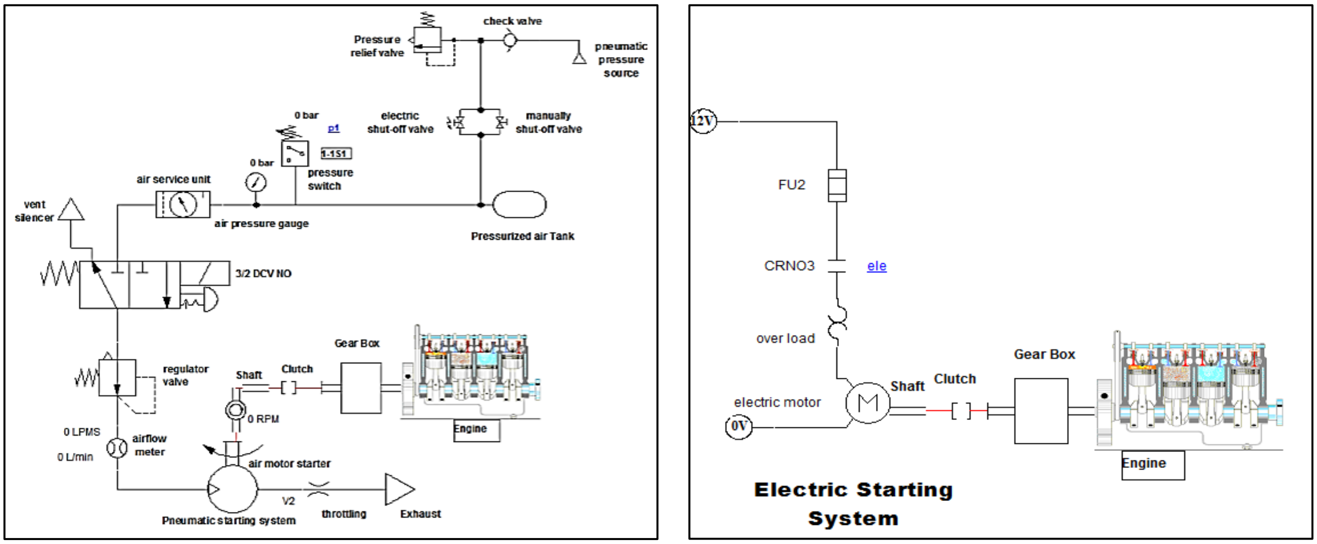
Usually, large combustion engines are started by means of pneumatic starting arrangements. The most common ways of starting a combustion engine with compressed air, are to use a pneumatic motor coupled to the engine flywheel or to inject the air directly into the engine cylinders through a valve in the cylinders head. The first type is the one used in small and medium-speed engines with limited space in the cylinder head for a starting valve, while the second used in large engines [4, 5, 6, 7]. Pneumatic starting engines are preferred for gas engines with a prechamber. Pneumatic starting systems for a gas turbine engine are discussed. Systems are reviewed from the standpoint of energy utilization, versatility, and reliability [8]. It is concluded that the auxiliary gas turbine compressor/air turbine starter combination is the optimum arrangement and it will continue to be the primary starting means in gas turbine engine applications. Regarding the response time and the flexibility, improving the turbine performance during the start-up phase is an important issue that should be taken into account by the turbine manufacturers. To analyze the turbine performance during the start-up phase and to implement novel ideas to improve its performance, modeling, and simulation of an industrial gas turbine during the cold start-up phase is investigated by using an integrated modular approach. During this phase, a complex mechatronic system comprised of an asynchronous AC motor (electric starter), static frequency converter drive, and gas turbine exists [9]. The start-up phase happens in the following manner: first, the clutch transfers the torque generated by the electric starter to the gas turbine so that the turbine reaches a specific speed (cranking stage). Next, the turbine spends some time at this speed (purging stage), after which the turbine speed decreases, the sparking stage begins, and the turbine enters the warm start-up phase. It is, however, possible that the start-up process fails at an intermediate stage. Such unsuccessful start-ups can be caused by turbine vibrations, issues with fuel spray nozzles, or the increase in the gradients of exhaust gases. For any reason, if the turbine can't reach the self-sustained speed and the speed falls below a certain threshold, the clutch engages once again with the turbine shaft and the start-up process is repeated. The effectiveness of the proposed approach in the detailed performance prediction of the gas turbine in the start-up phase was confirmed.

This paper investigates hybrid-starting systems (electric and pneumatic) for a vehicle engine. The study is extended to include a detailed comparison between the two concepts, and a detailed explanation of the design and implementation of the Electronic Control Unit (ECU) for the engine starting management. The objective is to give means for investigating, by using computer simulations, as a typical pneumatic and electric device relating safety to tractors and commercial vehicles (i.e., Lorries, tractors, and buses) to start the process of the starting system.

Adding an additional starting system that depending on another energy source has many advantages; such as avoiding the traffic delay in the case of the starting system failure, getting a more available number of starting cycles, and turning the vehicle off and on frequently during the idling; that reduces the fuel consumption and harmful emissions, and increase the battery and the electric starting motor lifetime. Moreover, depending only on the electrical starting system is not safe enough for tractors and commercial vehicles (i.e., Lorries, tractors, and buses) which work on area faraway maintenance center and are difficult to start by pushing or pulling like a small automotive. So; using a pneumatic system on the engine starting process is very effective; especially the infrastructure like compressors, piping,….etc., are already in place where the compressed air has other uses such as opening/closing the doors and/or braking system; so there is no need to build another system.

2. System Modeling

This paper focuses on a model of a whole pneumatic system; that is controlled by on/off solenoid valves and powered by a pneumatic motor and an electric starting system; that is powered by a DC permanent magnet motor. The proposed starting systems are shown in figure (1).



a b

Fig (1) - The proposed starting system

a: Pneumatic starting system; b: Electric starting system

2.1 Pneumatic Starting System Model

The main components in the pneumatic starting system are; a pressurized tank, a directional control valve, an air motor, and connecting air tubes. MATLAB/SIMULINK-SIMCAP R2013a tools are used for modeling and simulating the proposed system, figure (2) shows the layout model for the pneumatic starting system.

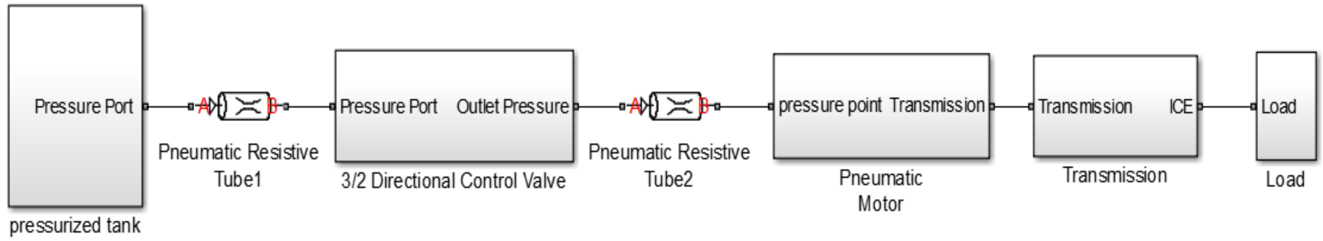


Fig (2) - Modeling of the pneumatic starting system

2.1.1 Air Tank Model:

Air is normally assumed to be an approximation of an ideal gas for values of pressure and temperature far from its critical point. In buses and commercial vehicles, pneumatic energy stored at a pressure up to 10.869 absolute atmospheric pressure in an existing air storage tank, which is initially designed for storing the service air on the bus [10]. The utilized simulant air tank model is illustrated in figure (3). Moreover, a standard block to model the fully pressurized tank with all properties is given in [11].

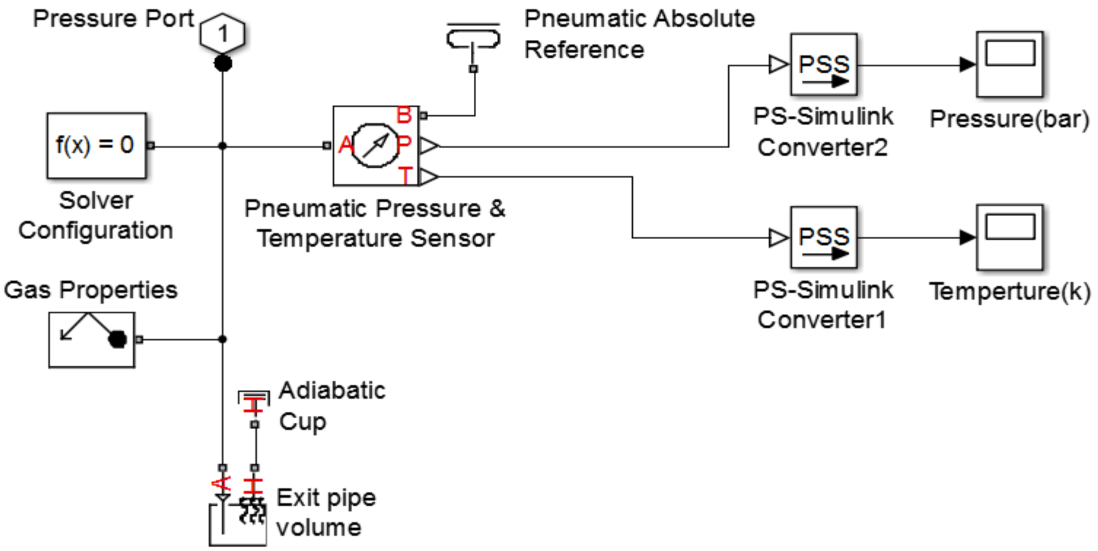


Fig (3) - Pressurized air tank model

2.1.2 Pneumatic Tubes Model:

Fluid dynamic equations for bends of pipe, filters, and valves are not within the scope of this paper, instead, all the resistances are converted into their equivalent lengths and the added heat due to the friction is neglected for its smallness. The pneumatic resistive tube SIMCAP block is utilized in the overall model.

2.1.3 Directional Control Valve Model:

A 3/2 ON/OFF solenoid directional control valve with an internally pilot has been used to satisfy the air motor operation in one direction. The valve model is divided into subsystems denoting the solenoid subsystem, the internally pilot and mechanical subsystem and the pneumatic subsystem are illustrated in figures (4) - (7) [12, 13, 14]. The delay in the valve dynamics will be modeled by adding a time delay to the valve solenoid.

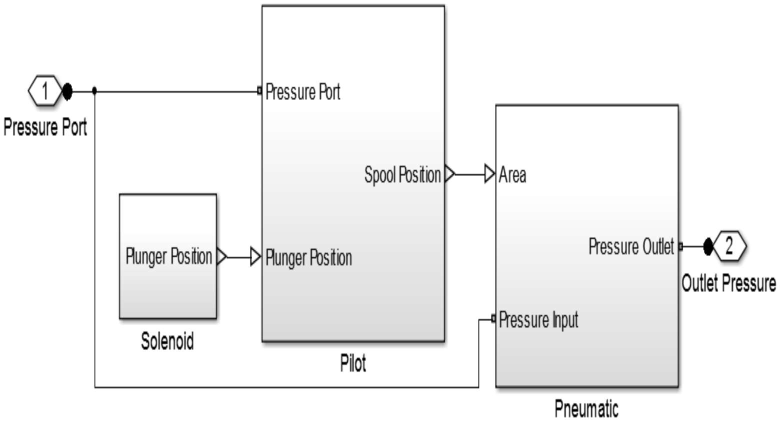


Fig (4) - Subsystems of directional control valve

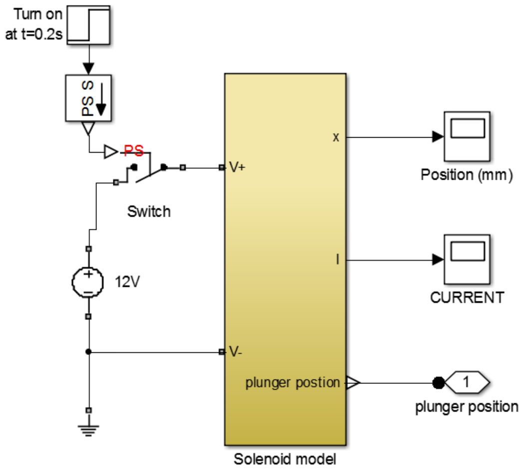


Fig (5) - Solenoid model

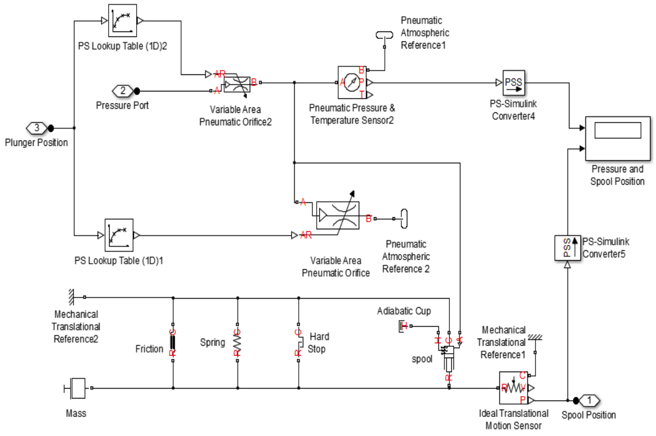


Fig (6) - Internal pilot and mechanical model

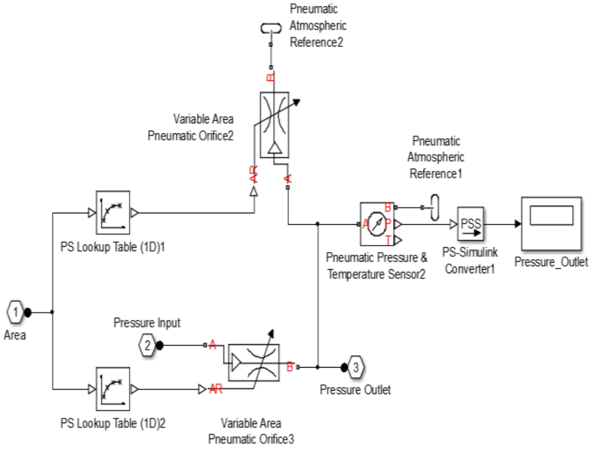


Fig (7) - Pneumatic subsystem model

2.1.4 Air Motor Model:

Employing the Simulink-SIMCAP tools [14], which gives the most accurate results, the pneumatic motor has been modeled by entering its data by the manufacturing catalog [15]at a specified pressure as follows.

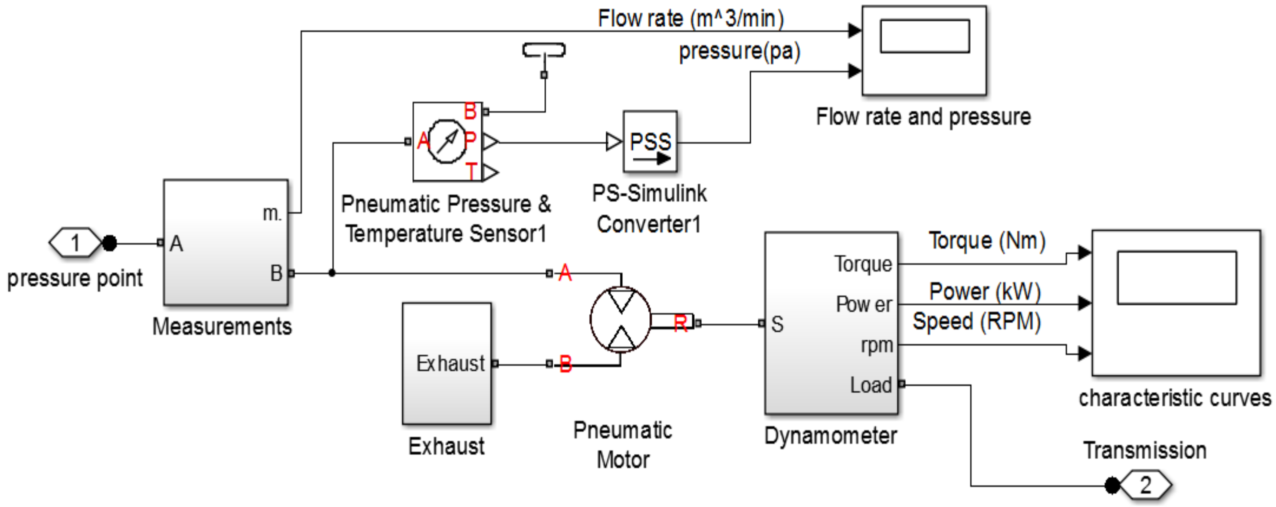


Fig (8) - Pneumatic motor model

2.1.5 Transmission System and Load Model:

The air motor is coupled with a pinion that engages with engine flywheel during stating operation to multiplier the torque flywheel. Also, the system has a unidirectional clutch to provide only positive torque to the engine flywheel and protects the starter motor from damage due to high engine speed once started. Using the SIMULINK-SIMCP blocks, the transmission system model is displayed in figure (9).

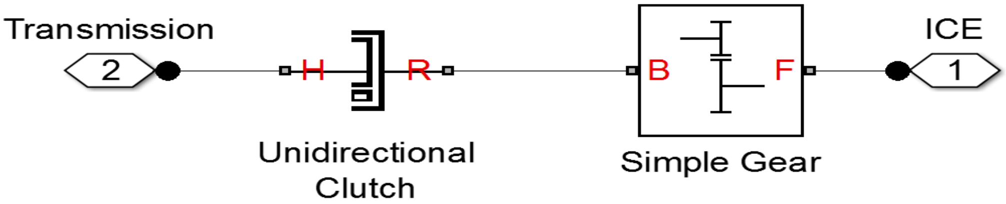


Fig (9) - Transmission system model

The vehicle IC engine modeling is out of our scope so; the engine load during starting has been modeled as inertia and friction loads. Using SIMCAP blocks, the obtained crankshaft model is presented in figure (10).

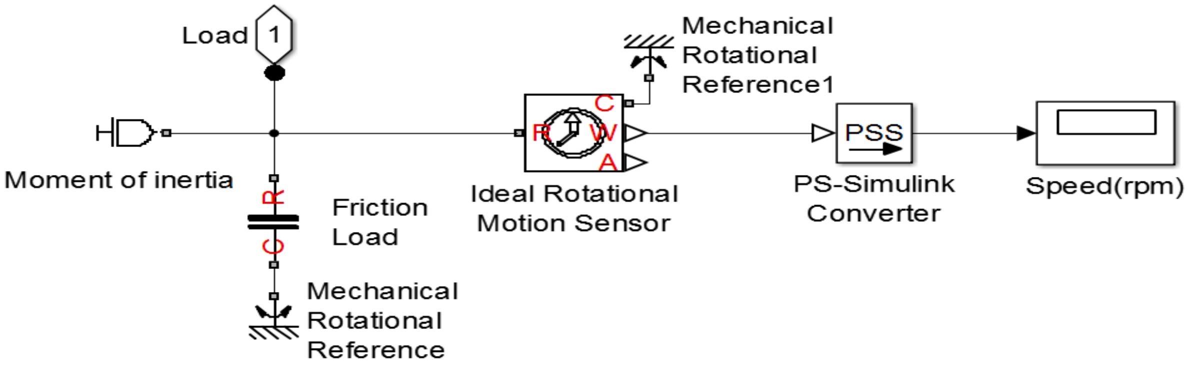


Fig (10) – System load model

2.2 Electric Starting System Model

In electric starting, the battery discharges current to an electric starting motor when the driver turns on the ignition switch to start. This causes engagement the pinion gear in motor with the teeth of the engine flywheel, causing rotation for the engine crankshaft to a higher speed than the minimum engine starting speed. The main components of the electric starting system are the battery, the electric motor, the transmission system, and the starting relay or solenoid. MATLAB/SIMULINK-SIMCAP R2013a tools are used for modeling and simulating the electric starting system, figure (11) displays the overall model for the electric starting system.

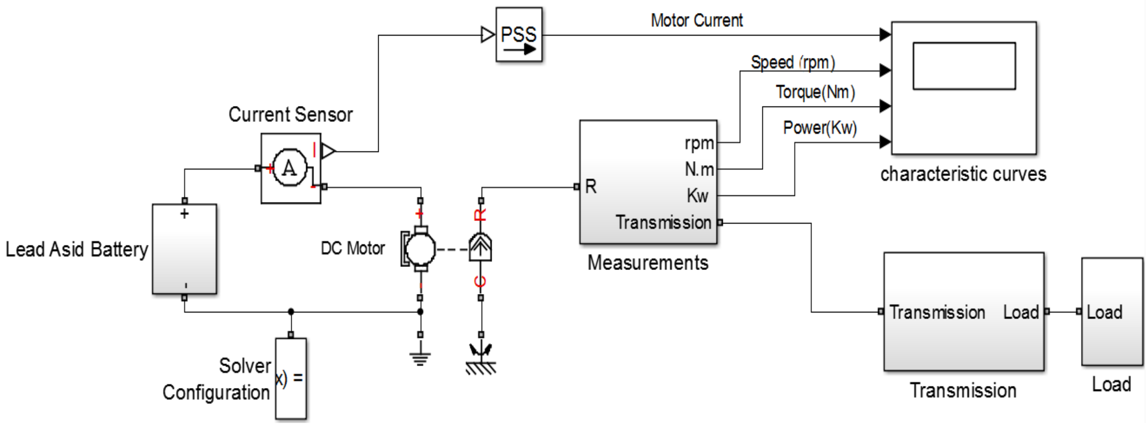


Fig (11) - Electric starting system model

2.2.1 Battery Model:

The used battery in an automotive is a lead-acid battery. The help of the SIMSCAPE toolbox [16] provides a 2V battery cell model based on a Jackey model [17] by this way the 12v lead-acid battery has been modeled as shown in figure (12)

2.2.2 Starting Motor Model:

The DC permanent magnet motor has been modeled with predefined Simulink SIM CAP blocks [18] [19].

2.2.3 Transmission System and Load Model:

The electric DC motor is coupled with a pinion that engages with engine flywheel during starting operation to amplify the flywheel torque. In addition, the system has a unidirectional clutch which enables the motor to provide only positive torque to the engine flywheel and protects the motor from damage due to higher engine speed once started. The transmission system and load were modeled as mentioned in modeling the pneumatic starting system.

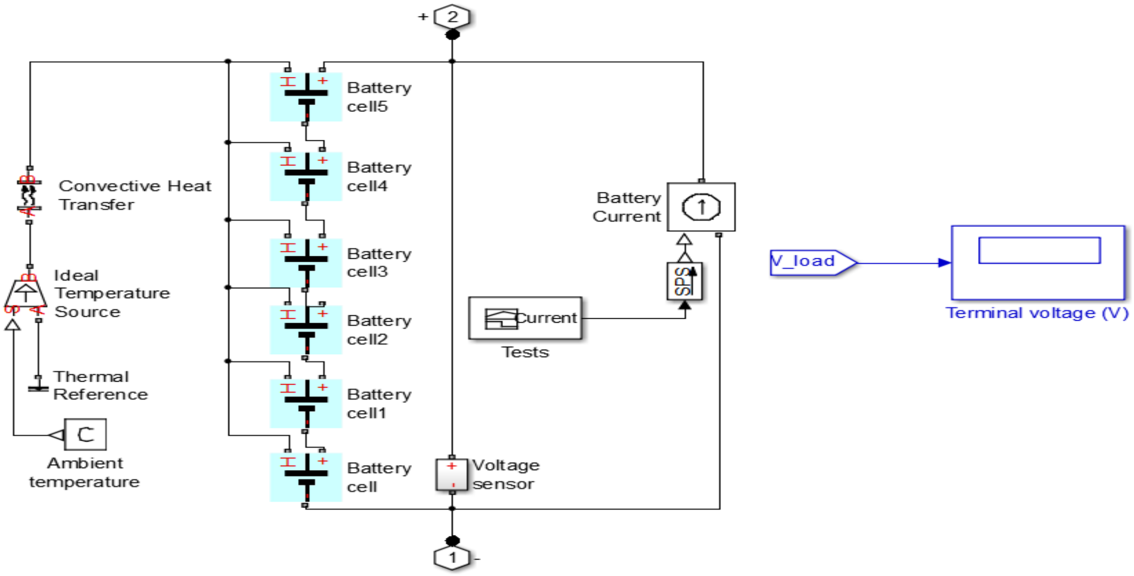


Fig. (12) – lead-acid battery modeling

3. System Investigation

3.1 Pneumatic Starting System Performance Investigation

The simulation of a pneumatic starting system displays the following characteristics. The pneumatic starting system and load parameters are given in the appendix.

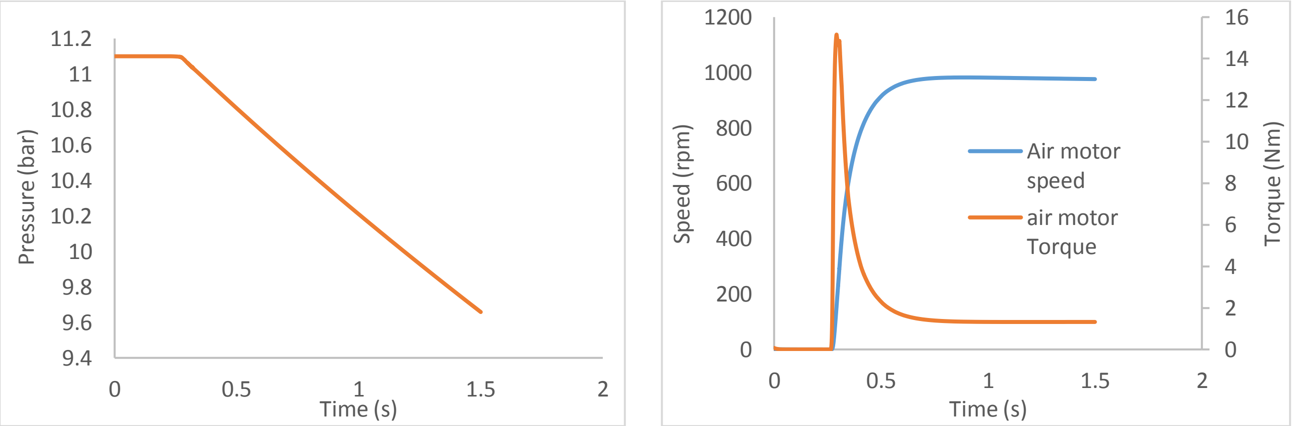


Fig. (13) – Time variation of the tank pressure **Fig. (14) - Characteristic curves for air motor seen from the load side**

From figure (13): the air pressure tank decrease during the starting period (1.5 s) from 11.1 bar to 9.6 bar. Figure (14) shows the characteristic curves for the air motor seen from the load side during the starting period (1.5 s). It can be seen that the air motor starting torque reaches to 15.16 Nm and the air motor starting speed reaches to 982.1 rpm in about (0.6 s).

3.1.1 The Number of Starting Cycles of The IC Engine by Compressed Air:

Air starting is highly reliable, where the torque available from air motors accelerates the engine to twice the starting speed in about half the time required by electric starters [20]. The air tank can be quickly recharged by a compressor which is driven by external power sources such as electric motors or directly by engines itself, or by a pneumatic regenerative braking system, or by using hand-pumped to starting pressure under emergency conditions. The air storage tanks must be protected against internal corrosion and freezing. To provide a specified number of starts without recharging the tank, the following formula has been used to determine the tank capacity [20].

$$V_T = \frac{VS * T * PA}{PT - PMIN} ,$$

Where: V_T =Air storage tank capacity, VS=Air consumption of the starter motor
T =Total cranking time required, PA=Atmospheric pressure, PT=Air storage tank pressure, P_{MIN} = Minimum air storage tank pressure required for cranking [20].

If five consecutive starts are required, we use five seconds for the first start where the engine is cold (worst starting system condition), and 1.5 seconds each for the remaining four starts, so the total cranking time of eleven seconds as shown in figures(15,16).

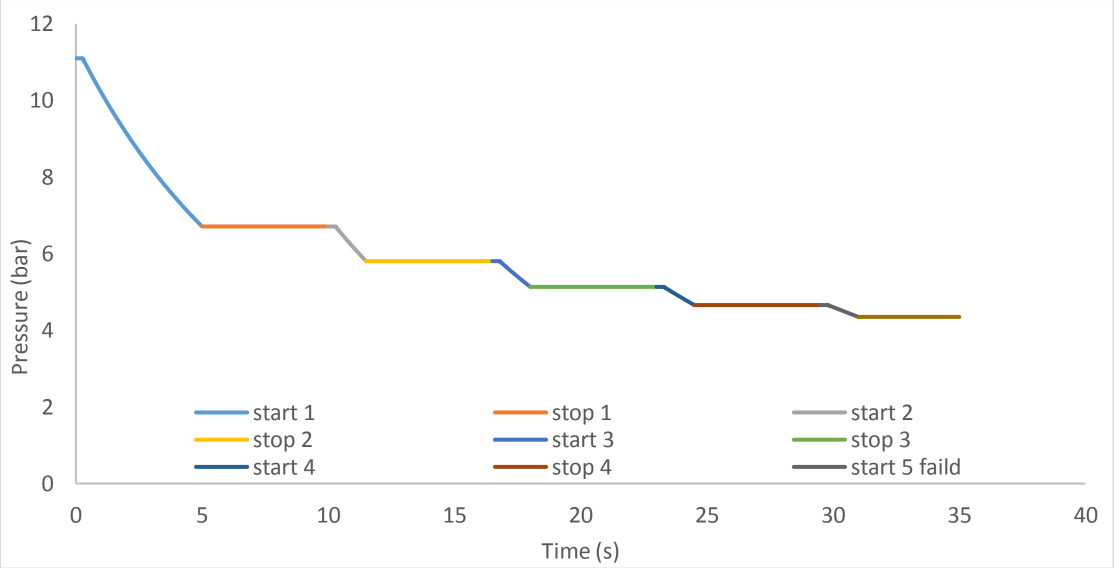


Fig. (15) - Pressure gradient during starting cycles

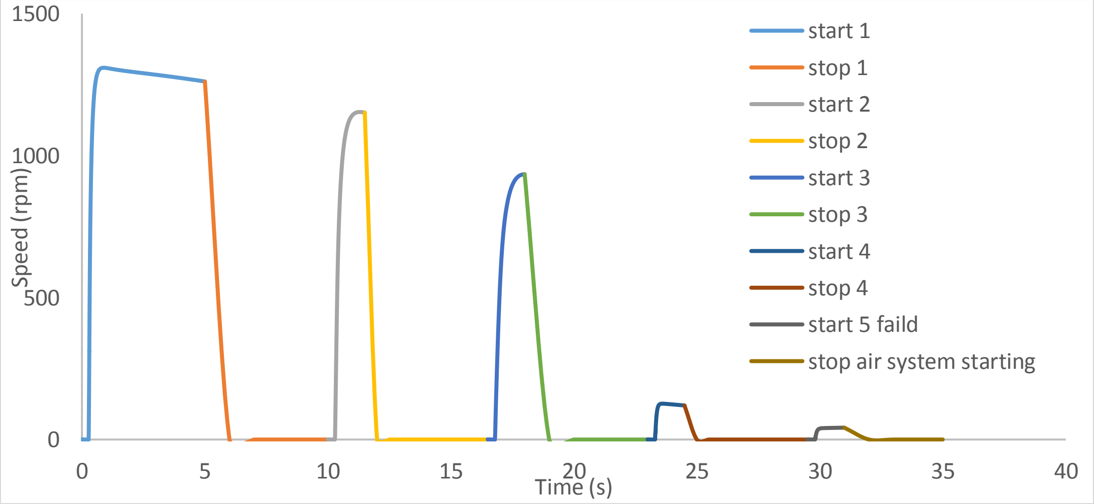


Fig. (16) - Speed gradient during starting cycles

For this time duration of start, we can start /stop the engine for 4 times and the system will fail and unable to start the engine any more times.

3.2 Electric Starting System Performance Investigation

The simulation of the electric starting system displays the following characteristics. The electric starting system and load parameters are given in the appendix.

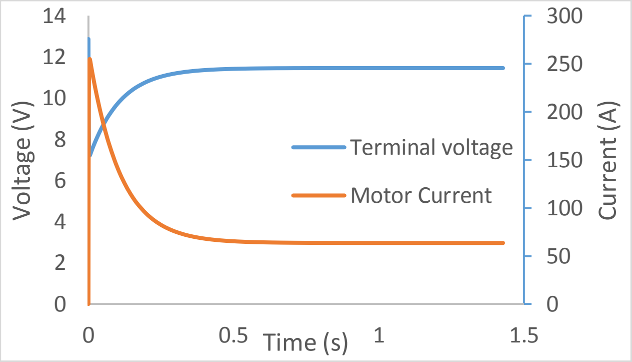


Fig. (17) - Battery voltage and the current drawn

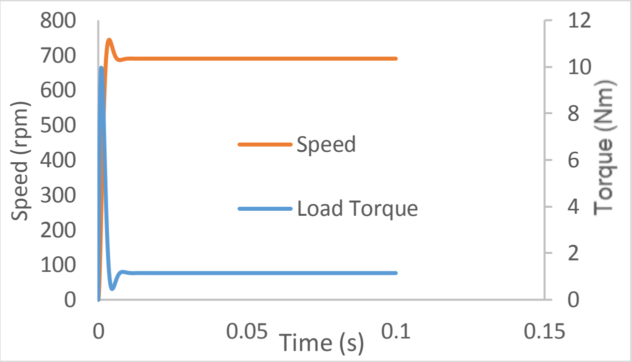


Fig. (18) -Characteristic curves for the DC motor seen from the load side

Figure (17) shows the battery voltage and the current drawn from it. It can be seen that the battery voltage reaches to 11.4 V with 63.5 A drawn current during the starting period (1.5 s). Figure (18) shows the characteristic curves for the electric DC motor seen from the load side. It can be seen that the electric motor starting torque reaches to 9.96 Nm and the electric motor starting speed reaches to 686.3 rpm in about (0.01 s). Through experimentation, the electric starter motor was able to provide enough torque to accelerate the crankshaft to speed higher than the minimum starting speed in 0.25s [21, 22].

3.3 Comparison of the Performance of Pneumatic and Electric Starting System

Through figures (14, 18) the pneumatic starting system is better performance than the electric starting system. The pneumatic motor starting torque increases about 52.2% than the electric motor and the pneumatic motor starting speed increases about 43.1% than the electric motor. Furthermore, the pneumatic starting period is larger than the electric starting system due to pressure build-up and delay valve dynamic but this delay time is not noticeable by the driver.

4. Conclusions

Starting the automotive IC engine by pneumatic and electric starting system has been modeled by using MATLAB / SIMULINK-SIMCAP R2013a.

The pneumatic starting system is capable of starting the automobile engine as the electric starting system with better performance higher than the electric starting system about 52.2% increase in starting torque and about 43.1% increase in starting speed.

The pneumatic starting period is larger than the electric starting system due to pressure build-up and delay valve dynamic but this delay time is not noticeable by the driver.

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Appendix

The modeling parameter values for a pneumatic starting system		
V_t	Air storage tank capacity	50 Liter
P_{tabs}	Air storage tank pressure	11.1 Bar (absol)
ω	The angular velocity (Rad/s)	[0,1379,4000,8000,12000,16000,20000,21655]rpm
T	Torque	[1.5,1.39,1.24,.982,.63,0.37,.123,0] N.m
Q	Air consumption	[462,516,709.2,804,954,1116,1140,1152] Lpm
ΔP	Differential Pressure	6.3 bar
i	Gear ratio	15
t_d	Time delay starting valve	0.2 s

The modeling parameter values for the load		
i	Gear ratio	15
J_L	Moment of inertia (Kgm 2)	0.0121kg.m2
T_B	Breakaway friction torque	3.8 N.m
T_c	Coulomb friction torque	1.3 N.m
μ	Viscous friction coefficient	3.5e-4N.m/(rad/s)

The modeling parameter values for an electric starting system		
R_a	Armature resistance	0.027 Ω
L_a	Armature inductance	0.000042 Henry
K_t	Torque constant	0.009037 N*m/A
B	Damping coefficient	0.00045 N*m/(rad/s)
J_{el}	Moment of inertia	0.000001kgm2