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# Aircraft Jet Engine Electrical Starting System

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**Abstract**

This paper presents the study and analysis of the parameters of aircraft electrical starting system by using multi-method multi-step starting process. The most important parameters of any starting system are the efficiency of the starting system, the duration time of the starting cycle, the starting torque and the current variation during starting operation, in addition to the size, weight and cost. The importance of each parameter is depending on the purpose of the aircraft as well as the jet engine included.

**Keywords:** Electrical starting system; jet engine; voltage control; field control

## منظومة بادئ التشغيل لطائرات المحركات النفاثة

**الخلاصة**

يهدف هذا البحث إلى دراسة و تحليل منظومة بادئ التشغيل لمحركات الطائرات النفاثة. إن كـلّ أنواع الطائرات في العالم, منها المدنية و العسكرية تحتوي على منظومات تشغيل مختلفة اعتمادا على نوع المحرك المستخدم في الطائرة أو الغرض من الطائرة نفسها.، ان منظومة بادئ التشغيل الكهربائي هي المنظومة الأكثر شيوعا في الاستخدام وخصوصا في الطائرات العسكرية و المدنية ذات الأحجـام المتوسطة والصغيرة.

إنّ العوامل الأكثر أهمية لنظام بادئ التشغيل الكهربائي هي، كفاءة النظام البادئ، الوقت المستغرق في عملية التشغيل، عزم البادئ في بداية التشغيل، درجة الحرارة القصوى التي يصل إليها التـوربين أثناء عملية بدئ التشغيل، وقيم التيارات اللحظية القصوى المسحوبة من المصدر أثنـاء عمليـة بـدئ التشغيل. كل هذه العوامل تم حسابها لكل طريقة من طرق السيطرة المستخدمة في الطائرات الحديثـة. حيث تم أثبات إن الطرق التي تحتوي على زيادة منتظمة بالجهد المجهزة أو الإضعاف المنتظم بالفيض المسلط هي أفضل أنواع السيطرة على منظومة البادئ مقارنتا بالطرق الأخرى المستخدمة.

### 1. Introduction

The engine starting system is designed for starting the engines and accelerating them to idle power, as well as cranking the engines and subjecting them to internal preservation and depreservation. The starting systems are used in both, civilian and military aircrafts. The parties of the technologies used for military applications are far more sophisticated than the one for civil aircraft. Generally, the starting procedure is basically always the same: a source of power provides the high torque needed to rotate the compressor and the turbine up to a speed at which adequate air passes into the combustion system. [1]

The starting systems which are used in modern aircraft are Electrical D.C Starter-Generator, Switched Reluctance Motor (SRM) Starter-Generator, Cartridge Starter, Air Starter, and Gas Turbine Starter. [2, 3]

Starting a gas turbine engine is somewhat different from starting a piston engine, although the basic

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operation is the same, they are just carried out in a different way. [2. 3]
A gas turbine engine must be spooled up and allowed to accelerate to a particular speed before fuel can be injected and ignited. Even after ignition, the engine still not producing enough of its own power to accelerate to idle speed.
For a dual-shaft jet engine type, it may be started by spinning up of one of the rotors or both rotors simultaneously. However, motoring over of both rotors simultaneously is a difficult construction problem associated with an increase in the weight of starting system. In view of above consideration, it is a common practice to rev up only one rotor, namely, the high-pressure rotor because the moment of inertia of this rotor is lower than that of the low-pressure rotor. [2, 3]
A part from the general requirements to the aircraft equipment, there are specific requirements to the starting systems:-[2, 3]

**a.** The starting systems should ensure a reliable starting and cold cranking of the engine on the ground as well as the in-flight starting in case of its inadvertent shut-down.
**b.** The system should insure self-contained starting i.e. provision should be made to start the engine from the air-born power source without the use of ground facilities. This requirement is important for fighters.
**c.** The starting system ought to have high efficiency of the starting process, i.e. the starting should consume small quantity of the power source energy which is very essential during a self-contained starting.
**d.** The starting cycle should be as short as possible. The length of the starting cycle is limited by the need in raising the aircraft combat readiness and to insure normal thermal conditions for engine operation.
**e.** The starter should have limited torque within initial several seconds in order to avoid dynamic overloads when eliminating the backlashes in the starter-to-engine shaft clutch gear.
**f.** The current variation through the starting process must have small fluctuations; therefore the life time of the batteries will be longer.
**g.** The starting should be automated. This requirement is imposed by the fact that a great number of operations are performed in certain sequence within a short period of time.
**h.** There should be a possibility for repeated starting and provision should be made for discontinuing the starting at any moment.
**i.** The starting system should constantly be ready for action.

To simplify and improve the starting process of the jet engine, the following condition must be materialized: [3]

**a.** The adjustable nozzle flaps should be opened to the maximum position.
**b.** The blades of the compressor guiding device should be sited to a position at which the air flow through the aircraft engines is reduced.
**c.** The throttle lever is moved from the cutoff position to the idle position.
**d.** The igniter must be enabled, so that when the starter circuit is closed, the igniter will begin to produce a spark.

**e.** The electric fuel boost pump must be activated to provide the require fuel pressure.

**2-Principles of Starting Operation**

In the process of starting gas-turbine engine, the loads or moments acts on the starter shaft are the Resultant Moments $(M_r)$ which is a function of rotational speed of the jet engine and dynamic moment $(M_{dyn})$ which depends on inertia moment $(J)$ of the revolving parts and the acceleration value $\left(\frac{dw}{dt}\right)$. Figure (1) represents the starting operation of any turbojet engine. The equation of moments of all effecting load given as: - [3]

$$M_m + M_t - M_{fr} - M_{assy} - M_c = 0 \quad \ldots(1)$$

Moment $(M_{fr})$ and $(M_{assy})$ are relatively small, it doesn't usually exceed 2-3%: practically these losses are not high, for this reason, $(M_r)$ is mainly determined as a difference between $(M_c)$ that is proportional to the square of the rotational speed, and $(M_t)$ which is proportional to the speed of rotation.

Practically, cutoff speed $(N_s)$ is equal to (70 %) of the idle speed of the jet engine $(N_{idle})$.

$(N_{start})$ Is the speed required before engine ignition and it is equal to (10-12) % of the idle speed.

$(N_{sp})$ is the balance speed at which the torque developed by the turbine is equal to the compressor moment of resistance.

$(N_s)$ is the cutoff speed, this speed should be at least 10 % above balance speed.

Starting cycle can be divided into three stages (I, II and III). These stages can be represented by three mathematical expressions as:- [3]

$$(\mathrm{I}) \bullet\bullet\bullet\bullet M_m - M_c - \frac{dw}{dt} = 0 \quad \ldots\ldots\ldots(2)$$

$$(\mathrm{II}) \bullet\bullet\bullet\bullet M_m + M_t - M_c - \frac{dw}{dt} = 0 \quad \ldots(3)$$

$$(\mathrm{III}) \bullet\bullet\bullet\bullet M_t - M_c - \frac{dw}{dt} = 0 \quad \ldots\ldots(4)$$

**3-Outlet Gas Temperature**

Turbine engines may be instrumented for exhaust gas temperature indication at locations before, between, or behind the turbine stages. Exhaust gas temperature is an engine-operating limit, and is used to monitor the mechanical integrity of the turbines, as well as to check engine-operating conditions. [4]

The maximum operating temperature of gas at the inlet to the turbine is stated by the refractoriness of material of the turbine blades and efficiency of cooling of their blades. In majority of contemporary jet engines having no special internal cooling of the turbine blades and of the turbine disk as well, this temperature does not exceed (850-900)$^{o}$C. [4]

The maximum stator outlet temperature or equivalent exhaust gas or blade metal temperature, inadvertent occurrence of which for periods of up to few seconds (during starting or acceleration process of the engine), has been agreed not to require rejection of the engine from service or maintenance action (other than to correct the cause).

Figure (2) shows the engine's thermal behavior during starting operation. Maximum temperature is reaches during starting and decreases with the increase of the engine speed to reach the normal value at idle speed. [5]

At the beginning the temperature is rise without fuel supply, this increase is caused by the compression in the compressor stages and the temperature is rises sharply when the fuel is ignited in the combustion chamber, and during acceleration the temperature decreases with increase the rotational speed of the engine rotor. [5]

**4-Aircraft D.C Electric Starter**

There are two types of DC starters, first type utilizes an electric motor for starting only, and the second employs a starter which becomes a generator when the engine is operating at normal speeds as shown in figure (3). [3]

When the starter-generator starts from rest and runs up the jet engine to a cutoff speed $w_s$ , its electrical supply must furnish the energy $\left(Q = \frac{1}{2} J w_s^2\right)$ stored in the system inertia $(J)$. The energy loss in the armature-circuit $\left(I_a^2 R_a^2\right)$ resistance, whether or not it includes an external starting rheostat, is equal to the kinetic energy stored in the acceleration process and it can be seen that the energy losses is independent of the Armature circuit resistance.[3]

There are many methods to reduce the energy losses during starting process such as reducing the moment of inertia of the engine rotor and step or smooth rise of applied voltage and stepped or smooth reduction of applied field but also the starting time will be increases.

The efficiency $(h)$ and the starting time $(t_s)$ for each method: direct starting, rheostatic starting, stepped rise in applied voltage starting, smooth rising in applied voltage starting, stepped reduction in applied field starting and smooth reduction in applied field starting are shown in the following relations. [3]

***Direct starting:***

$$h = \frac{w_s}{2w_o} * 100\% \quad \text{........ (5)}$$

$$t_s = t_{elemech} \ln \frac{w_o}{w_o - w_s} \quad \text{........ (6)}$$

***Rheostatic starting:***

$$h = \frac{w_s}{2w_o} * 100\% \quad \text{......... (7)}$$

$$t_s = t_{elemech} \cdot \frac{w_s}{w_o - w_s} \quad \text{... (8)}$$

***Stepped rising in applied voltage:***

$$h = \frac{w_s}{2w_o - \frac{n-1}{n} w_s} * 100\% \quad \text{... (9)}$$

$$t_s = n * t_{elemech} \ln \frac{w_o - \left(\frac{n-1}{n}\right) w_s}{w_o - w_s} \quad \text{...(10)}$$

***Smooth rising in applied voltage:***

$$h = \frac{w_s}{2w_o - w_s} * 100\% \quad \text{....(11)}$$

$$t_s = t_{elemech} \cdot \frac{w_s}{w_o - w_s} \quad \text{.... (12)}$$

***Stepped reduction in applied field:***

$$h = \left(\frac{n}{n+1}\right) * \frac{w_s}{w_o} * 100\% \quad \text{...... (13)}$$

$$t_s = t_{elemech} \sum_{m=1}^{n} \left(\frac{m^2}{n^2}\right) \ln \frac{w_o - \left(\frac{m-1}{m}\right) w_s}{w_o - w_s} \quad \text{..(14)}$$

***Smooth reduction in applied field:***

$$h = \frac{w_s}{w_o} * \frac{b^2}{b^2 + 1} \quad \text{...... (15)}$$

$$t_s = t_{elemech}\left[\frac{1}{b^2}\left(\ln\frac{w_o}{w_o - w_s} + 0.5\frac{b^2 w_s - w_s}{w_o - w_s}\right)\right] \quad ...(16)$$

Where ($t_{elemech}$) is the mechanical time constant of the starter and the rotor of the jet engine and (b) is the maximum applied field to nominal applied field ratio.

Figures (4 to 9) show the speed and the starter current during starting operation for each method. [3]

As it is shown the best efficiency is obtained by using smooth reduction in field current and smooth increase in armature voltage. This can be done if the power supply can give the voltage to the system with smooth increasing and after the voltage reaches its final available value, the system will begin to reduce the field current until the engine reaches the cutoff speed. [3]

Figure (10) shows all requirements for D.C drive control where the armature and field of the starter are fed from separate controllable power supplier.

Rotating generators have been the common choice in the past, forming the well known Ward Leonard scheme, but after brief interludes by magnetic amplifiers and mercury arc converters, power electronic converters employing solid state semiconductor switching elements (various types of thyristors or power transistors) are now the standard solution. Practically, high power semiconductor devices are used in armature circuit because of high current level in this circuit and low power semiconductor devices are used in field circuit. [6]

**5- Simulation and Results**

Figure (11) shows the block diagram of armature control regime using the current controller D.C drive. [7]

The purpose of this circuit is to drive the engine from rest (zero speed) to a speed equal to $\left(\frac{w_s}{b}\right)$. This circuit gives the starter a voltage equal to (0.5 Vn) to produce a sufficient starting torque at the beginning of the starting process, and also gives the system a linear acceleration by keeping the torque at constant level ($I_a$=constant). [7]

If a power electronic converter is employed as armature supply, a proportional-integral controller (PI) is adequate to be used. The main purpose of the current controller is to linearized the plant and prevent overloading the motor by using a single integral.

The advantages of using (PI) controller are the low number of design parameters and the fact that the controller parameters can be easily be related to performance measures.

Actuator or power conversion is the device used for controlling the provided power to the starter. Chopper circuit with power MOSFET is used to control the starter current.

Figure (12) shows the behavior of the system during armature control range. [7]

Figure (13) shows the block diagram of dc drive in armature voltage and field weakening regime. The driver in this region is controlled by the two quantities, armature voltage and field current. For good utilization, it is important that the starter should be supplied either with maximum field voltage, and increase the armature voltage or with maximum armature voltage, and reduced field current. Since the driver is operate alternately in both of these regions, it is appropriate to choose a control strategy which fulfills both requirements and permits a continuous and automatic transition from one operating to the other. A feed-back signal for the induced voltage (e.m.f) can be reconstructed from the measured armature voltage and current according to the voltage equation

$e.m.f = V_a - R_a I_a = K I_f w$ and an analogue computing circuit may be used for this purpose.

Figure (14), (15) shows the behavior of the above system where figure (14) shows the current-speed c/c and figure (15) shows the armature voltage-field current c/c.

This starting system consists of three stages:

**a.** The First Stage: - begins at (t=0) to ($t=t_1$), at this stage, the voltage is constant and equals to $\left(\frac{1}{2}V_n\right)$, and the flux is constant and equals to $\left(\Phi = b \cdot \Phi_n\right)$, and the system operates as a direct starting.

**b.** The Second Stage: - begins at ($t=t_1$) to ($t=t_2$), at this stage the voltage varies from $\left(V = \frac{1}{2}V_n\right)$ to $\left(V = V_n\right)$, and the flux is constant and equals to $\left(\Phi = b \cdot \Phi_n\right)$, the system is operating as a smooth variation in the power supply voltage.

**c.** The Third Stage: - begins at ($t=t_2$) to ($t=t_s$ ), at this stage the voltage of the power supply is constant and equals to (Vn), the maximum available value of power supply voltage, and the magnetic flux is varying from its maximum value to the nominal value (decreases). The flux must reach to its minimum value at the moment when the speed reaches to $(w_s)$

Equation (17), (18), (19) and (20) represent the starting efficiency and starting time for each stage. [8]

$$h = 3\frac{w_s^2}{\left(w_o w_2 - 6 w_1 w_2 + 3 w_1^2 + 3 w_2^2 + 3 w_o w_s - 3\frac{w_o w_2^2}{w_s}\right)} * 100\% \quad \text{.......(17)}$$

$$t_s = t_1 + t_2 + t_3$$

$$t_1 = \frac{1}{9} t_{ele} \ln \frac{w_o}{w_o - 6 w_1} . \quad \text{....(18)}$$

$$t_2 = \frac{1}{9} t_{ele} \left( \frac{w_2 - w_1}{\frac{1}{6} w_o - w_1} \right) . \quad \text{..... (19)}$$

$$t_3 = \frac{1}{2} t_{ele} \left( \frac{w_s - \frac{w_s}{b^2}}{w_o - w_s} \right) \quad \text{... (20)}$$

For the maximum efficiency, the period of each stage must be optimized to reach the maximum efficiency, so that when $\left(w_s = 0.7 w_o\right) and \left(b = 3\right)$ then:

$$w_2 = \frac{w_s}{b} = 0.2333\, w_o$$

$$w_1 = w_2 - \frac{\frac{1}{2} w_o}{b} = 0.06667\, w_o$$

Where $w_1$ is the speed at the end of stage one, $w_2$ is the speed at the end of stage two and $w_s$ is the cut off speed (i.e. the speed at which the starter is disconnected from the jet engine).

**6-Conclusions**

**a.** When the starting system is controlled by rheostatic control method, the los.ses will increased and cause a low efficiency starting system and long starting time.

**b.** The efficiency of any starting system is depends on the value of the cut of speed, increasing this value will tend an increasing in the efficiency of the starting system and maximum efficiency for any starting system is obtained when cutoff speed is equal to steady state speed.

**c.** The starting time for any starting system is depends on the acceleration value and the magnitude of the cut of speed. When cutoff speed is equal to steady state speed, the starting time will be very long because the speed is raise exponentially.

**d.** No effect for any additional resistance in the armature circuit on the starting efficiency but it will affect the starting time because the electromechanical time constant is directly proportional to the additional resistance.

**e.** When field control starting method is used, the ratio of the maximum field value to the nominal field value (b) is very important. This ratio affects directly the starting efficiency, starting time and starting torque. The only limit is the size and weight of the magnetic circuit which they are increase directly with this ratio.

**f.** When smooth armature voltage rise control method is used, the best method to control the supply voltage is by use power electronics devices, because the output power is approximately equal to the input power.

**g.** When a multi control method is used, the values chosen for the affects directly the efficiency and inversely the starting time.

A comparison between the starting methods is shown in table (1).

## 5- References


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**[2]** "Fundamentals of Aircraft Power Plants ", FM-1-506, Washington DC, 1990.

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**Table (1)Types and c/c of each starting method**

| parameters | Starting efficiency | | Starting time | |
|---|---|---|---|---|
| | Voltage | field | Voltage | field |
| One step | 35 % | 35 % | 1.2 $t_{elemech}$ | 1.2 $t_{elemech}$ |
| Two steps | 45.5 % | 46.7 % | 1.54 $t_{elemech}$ | 1.1 $t_{elemech}$ |
| Three steps | 46.7 % | 52.5 % | 1.72 $t_{elemech}$ | 1.05 $t_{elemech}$ |
| Smooth rise in (v) | 53.8 % | | 2.33 $t_{elemech}$ | |
| Smooth reduction in field | 63 % (at b=3) | | 1.17 $t_{elemech}$ | |

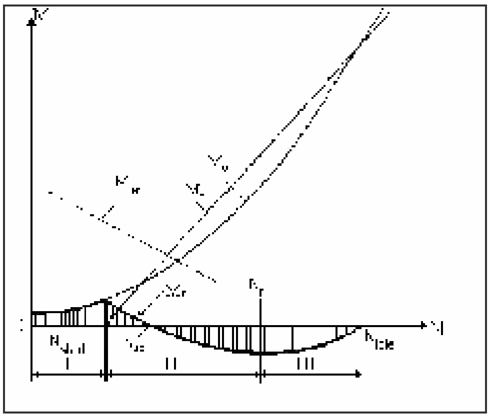

**Figure (1) Starting operation of the turbo jet engine**

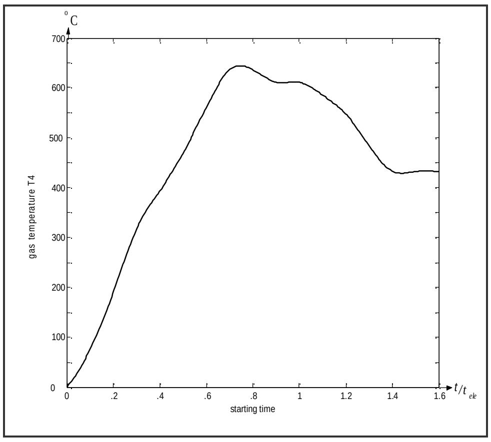


**Figure (2) Outlet Gas Temperature**

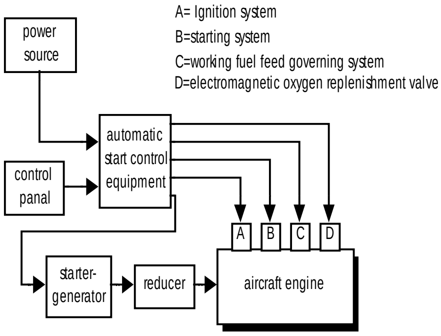


**Figure (3) Structural diagram of GTE starting system with Starter-Generator**

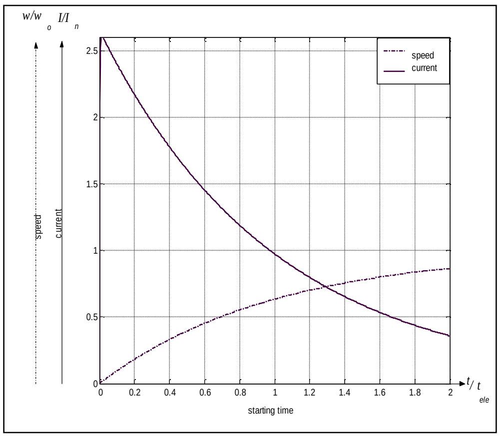


**Figure (4) Direct starting**

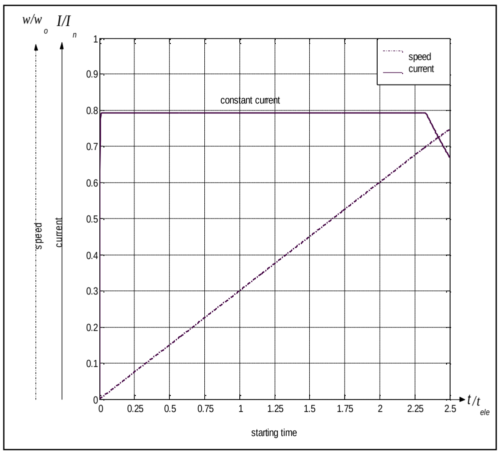


**Figure (5) Rheostatic starting**

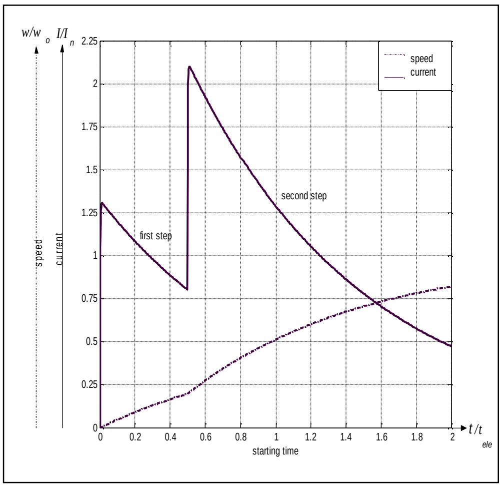


Figure (6) 2 step voltage rise starting

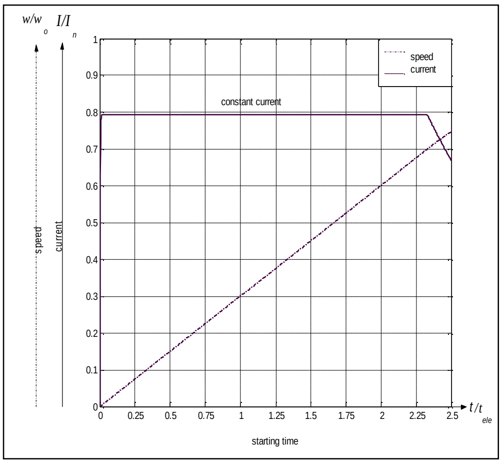


Figure (7) Smooth voltage rise starting

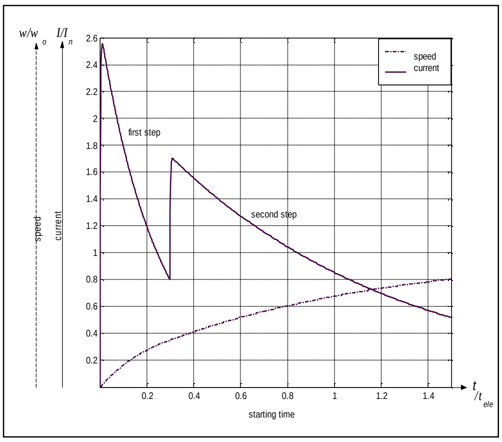


Figure (8) 2 step field reduction starting

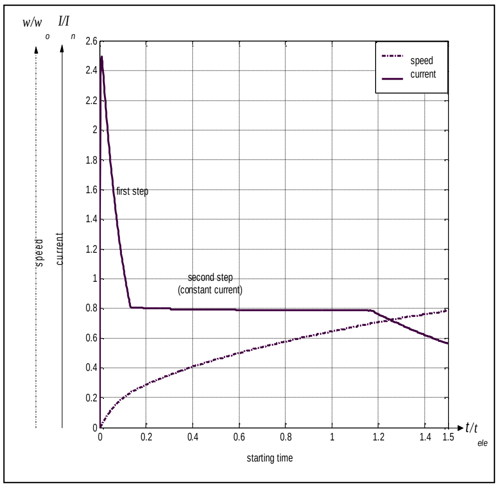


**Figure (9) Smooth field reduction starting**

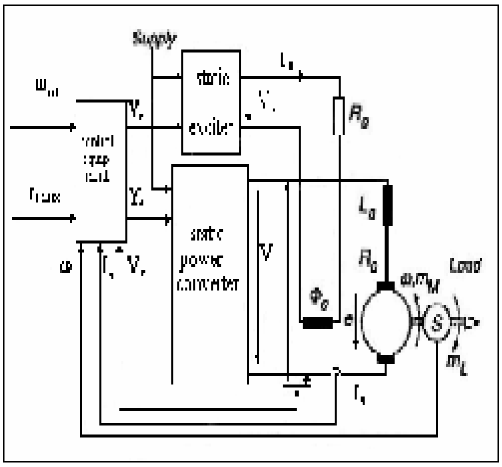


**Figure (10) General schematic of D.C drive control [6]**

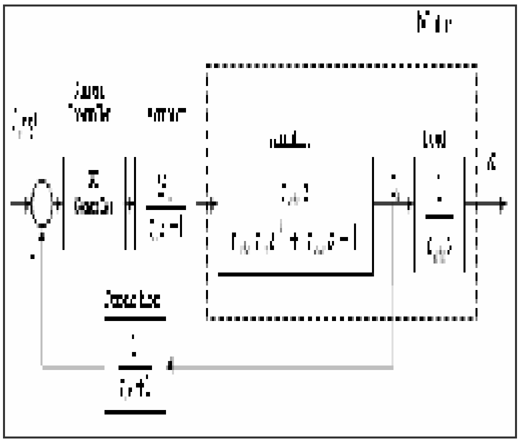

**Figure (11) Voltage control – current controller [7]**

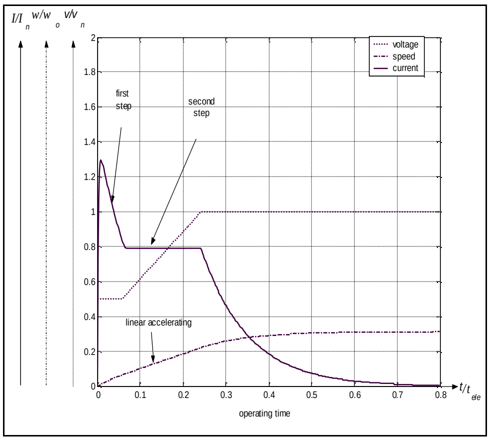


**Figure (12) Armature voltage control range**

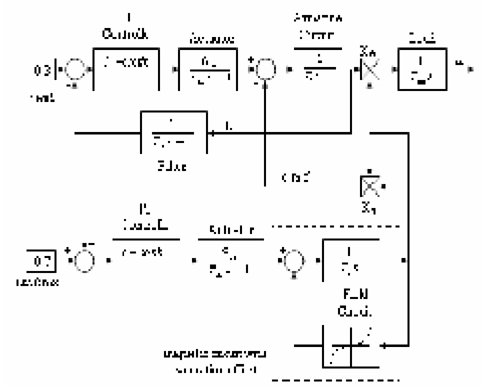

**Figure (13) Block diagram D.C drive in the armature and field weakening regime [8]**

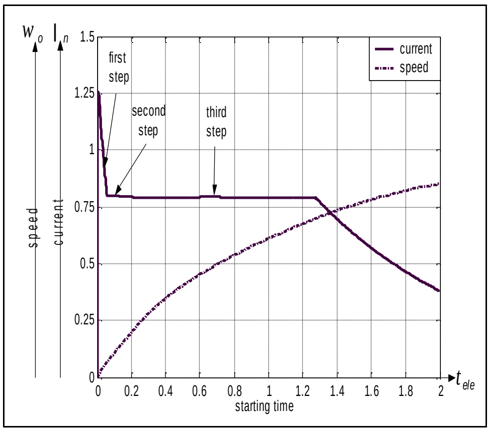


**Figure (14) Current-speed c/c of smooth variation in field and voltage ($t_1 =$0.057, $t_2 =$0.18 and $t_3 =$1.04)**

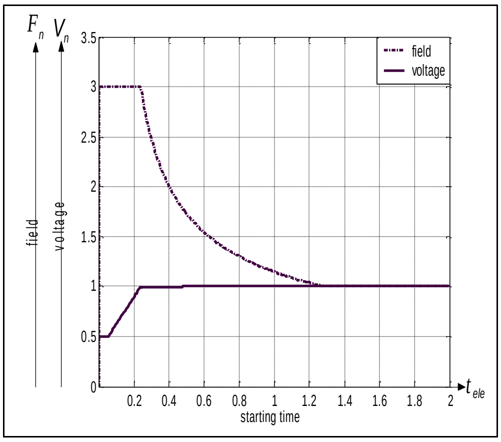


**Figure (15) Armature voltage-field current c/c of smooth variation in field and voltage**