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Electric Machines and Power Electronics: DC Machine Characterization

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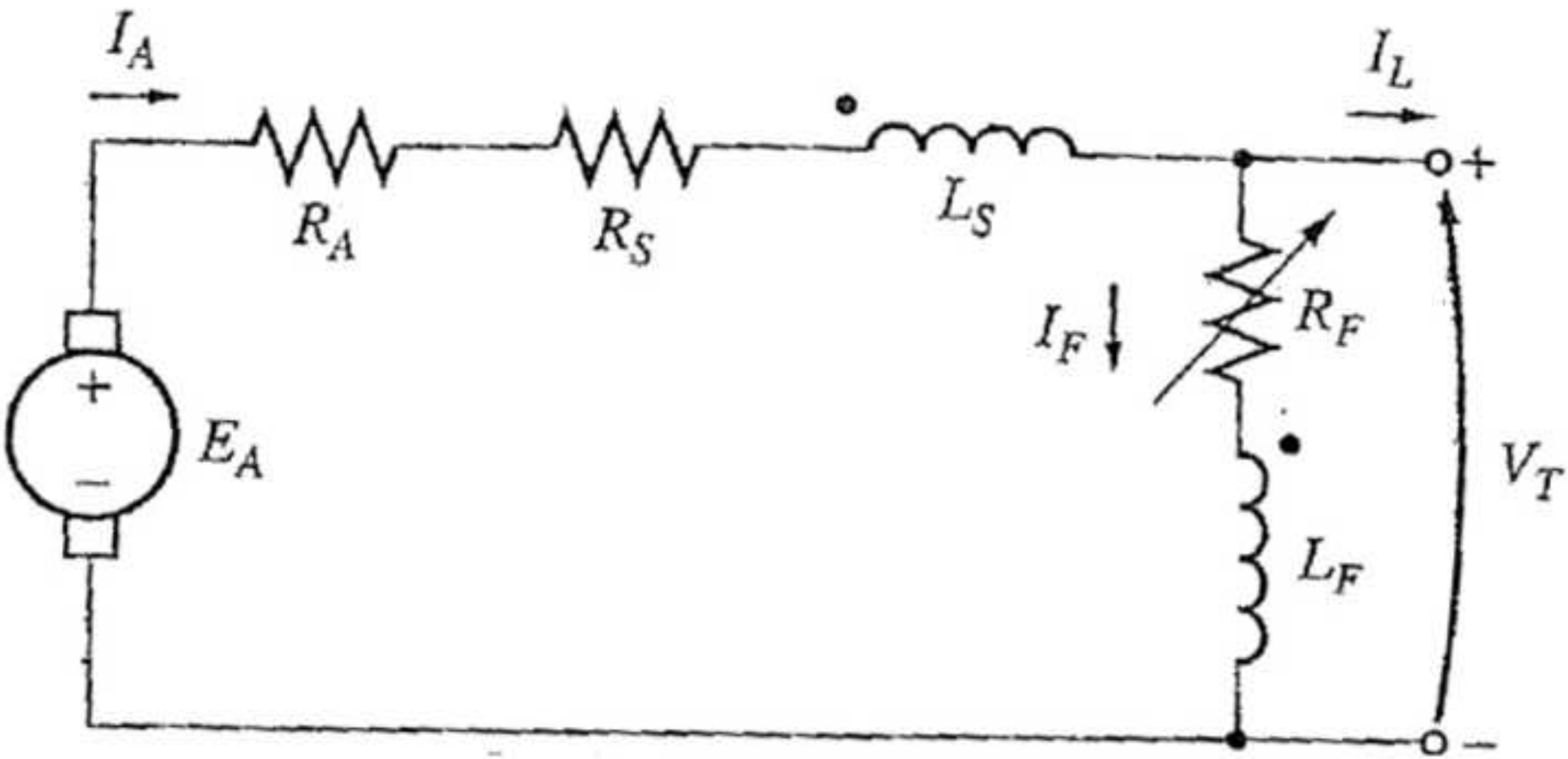

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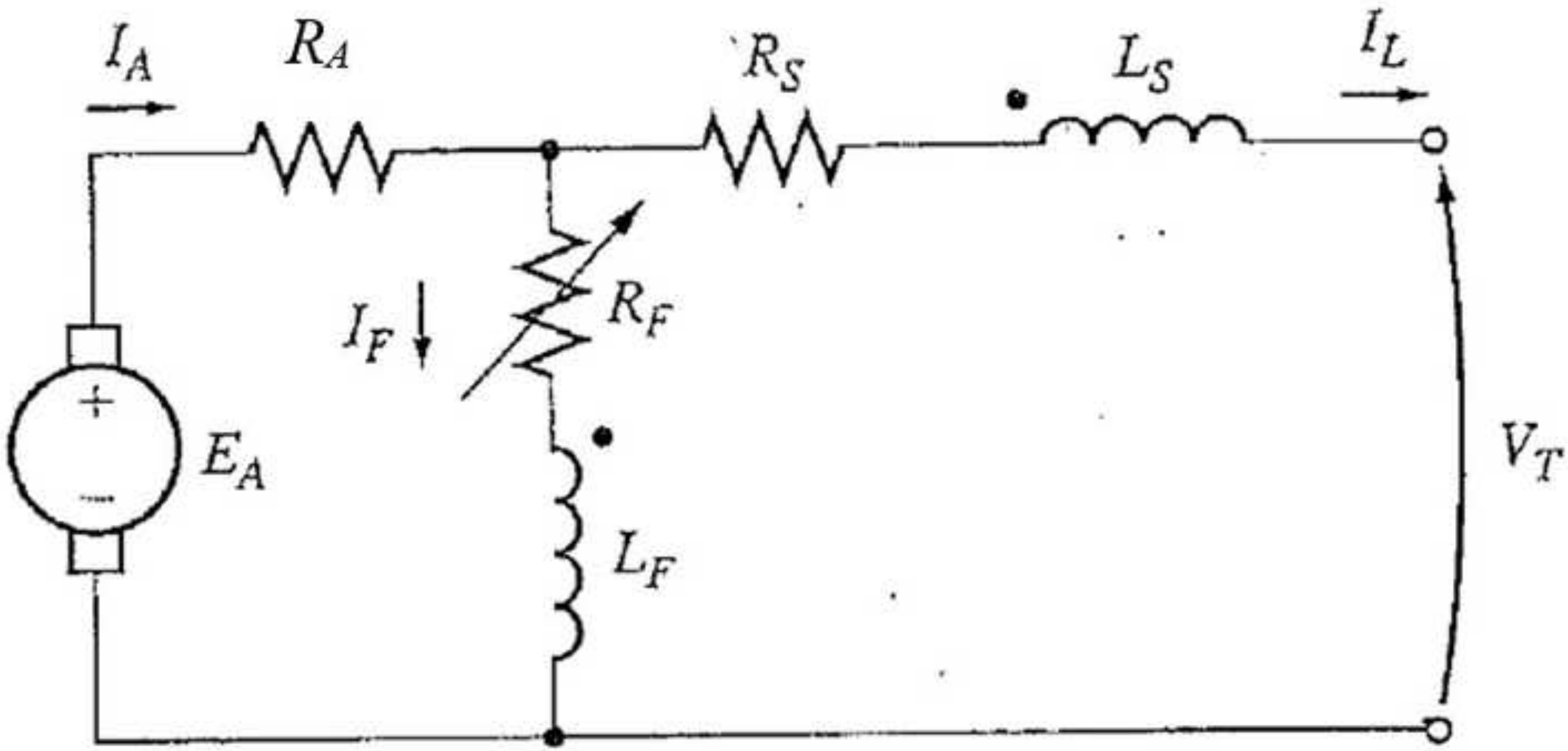

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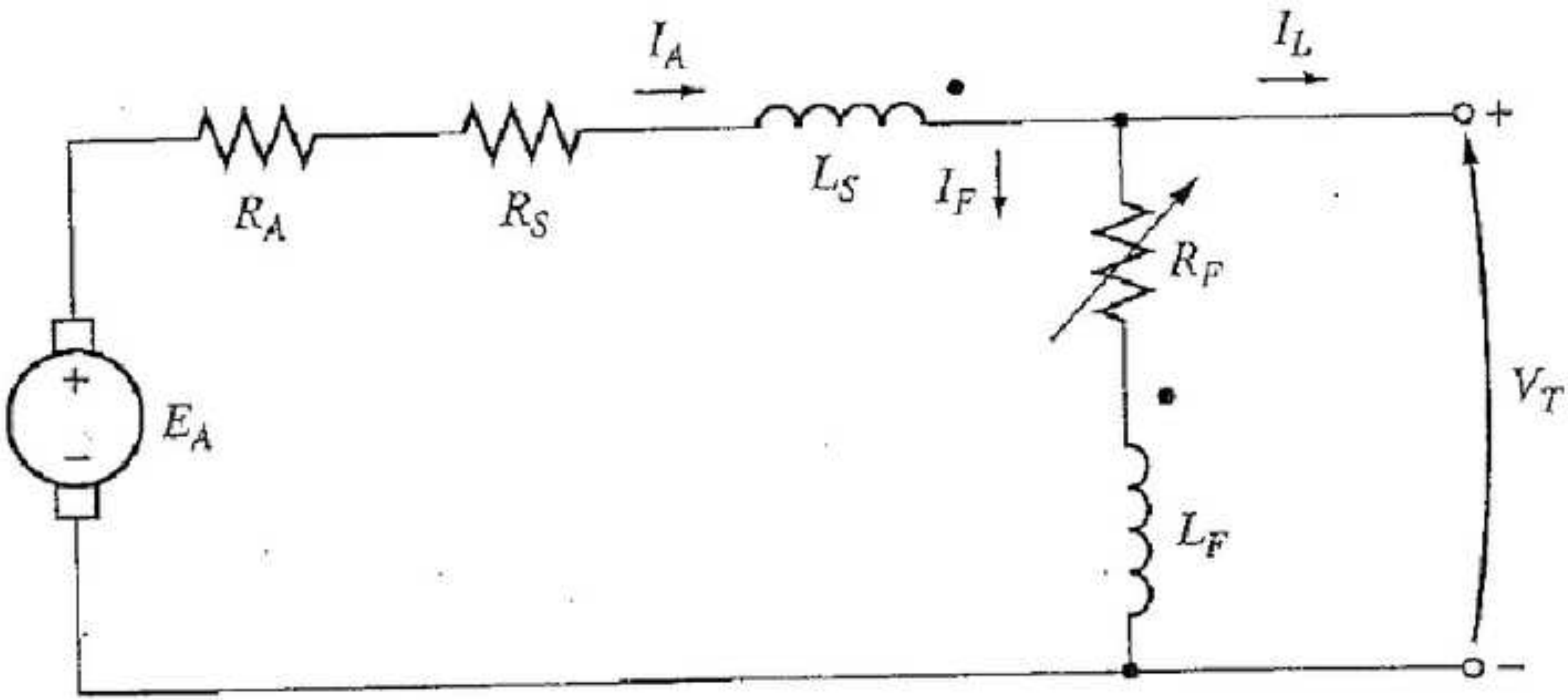

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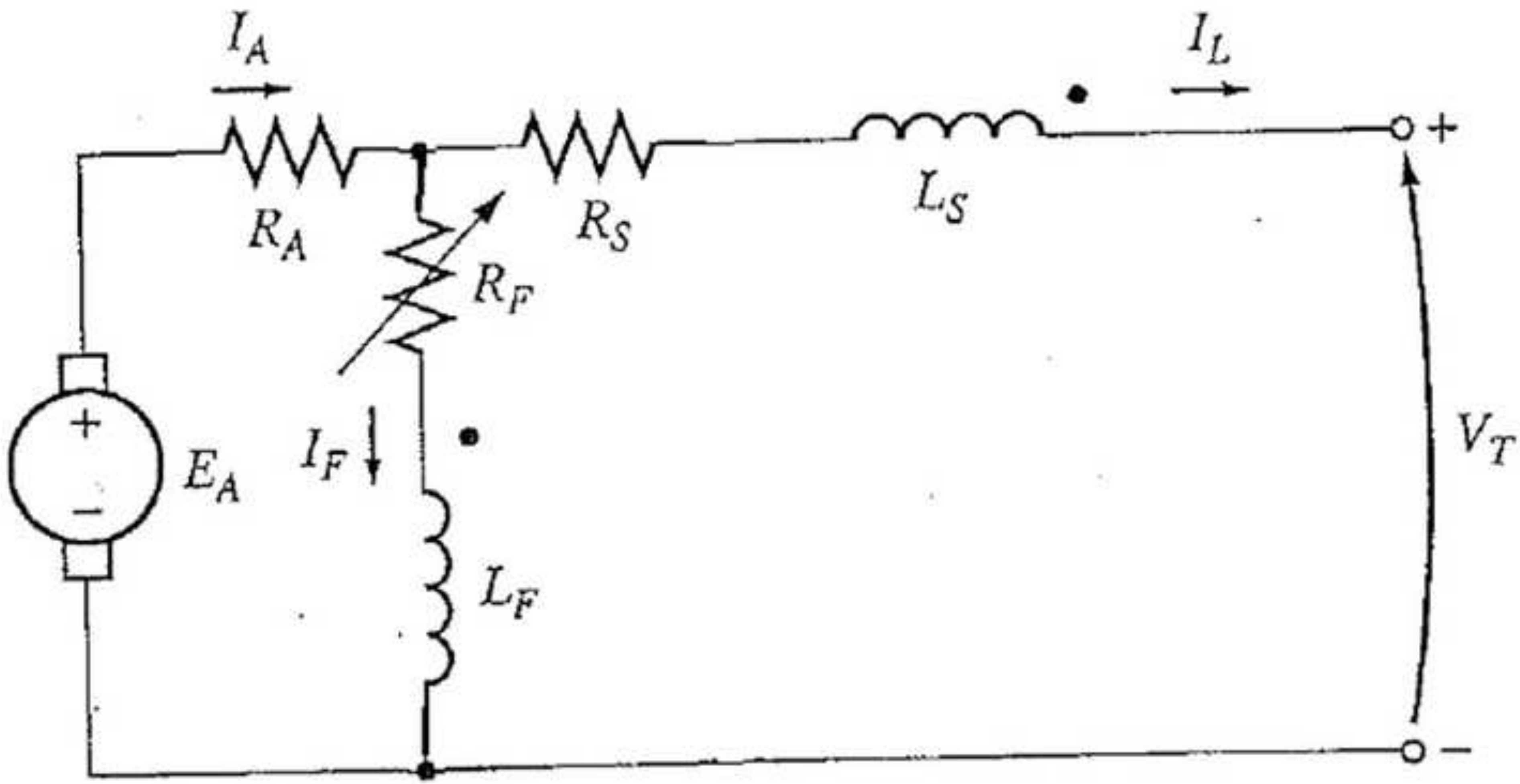

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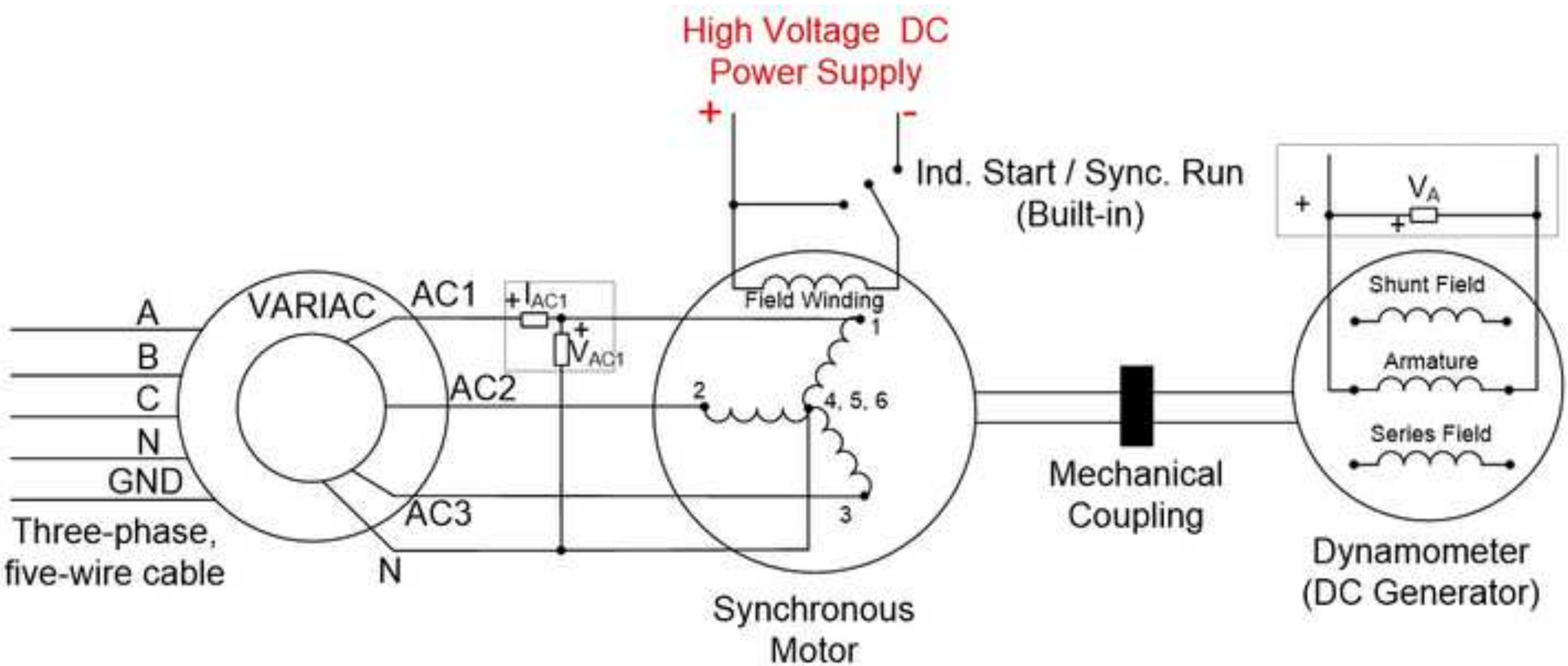

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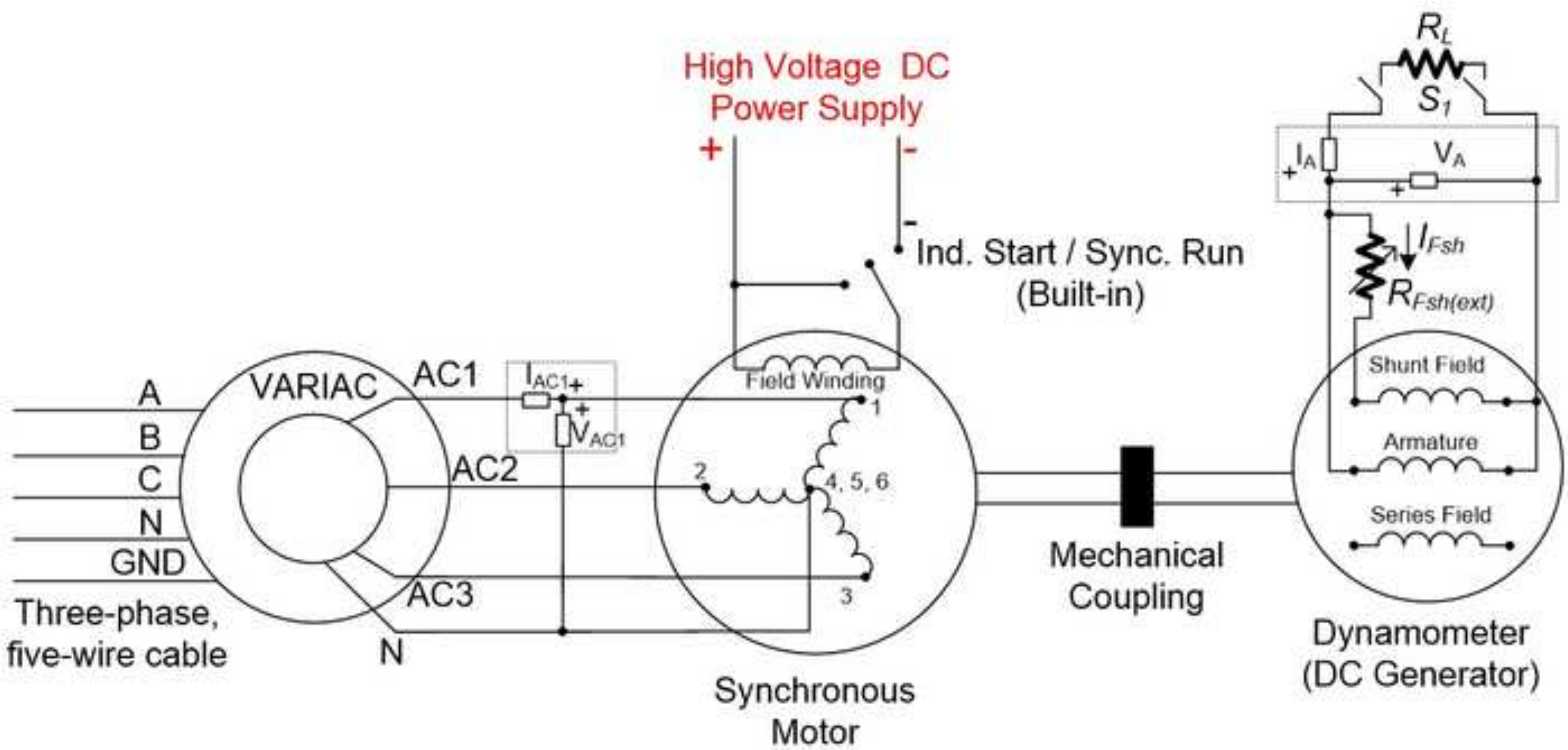

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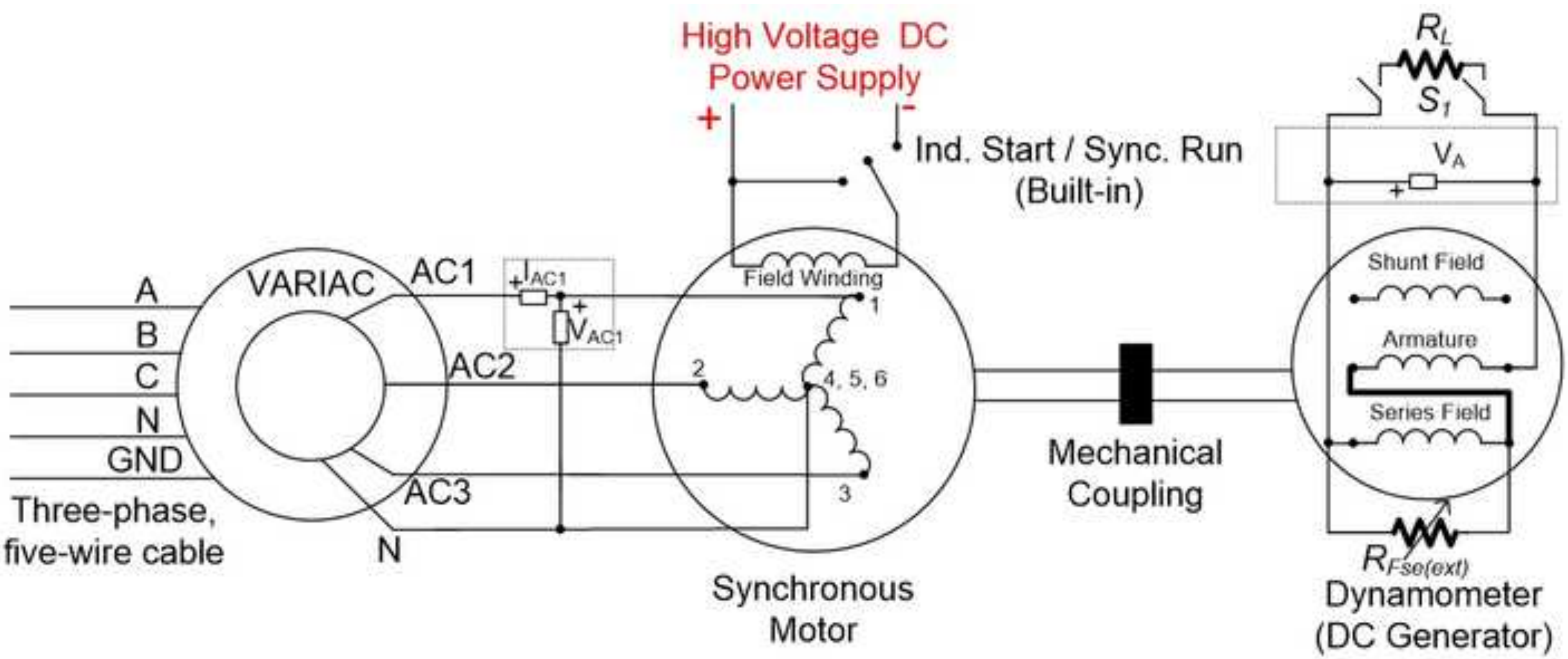

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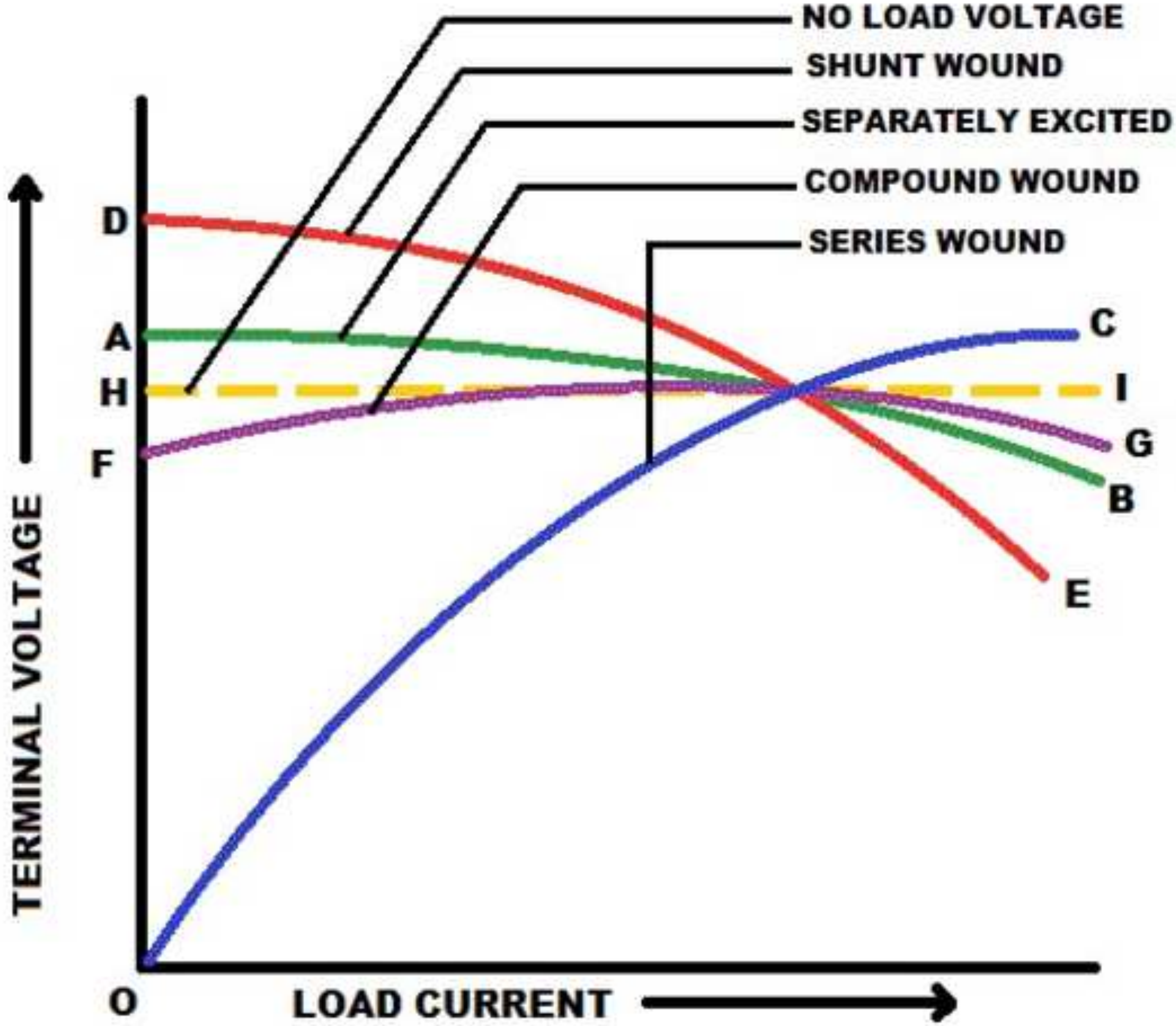

PERFORMANCE CURVES OF DC GENERATORS

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Electrical Engineering Science Education Title: Electric Machines and Power Electronics: DC Machine Characterization

Overview

The objective of this experiment is to test two main DC machine configurations: shunt and series. Tests are intended to estimate the residual flux in the machine and to study the no-load and loading characteristics of different configurations.

~~Introduction~~

The DC machine operates with DC currents and voltages compared to an AC machine which requires AC currents and voltages. DC machines were the first to be invented and utilize two magnetic fields that are controlled by DC currents. The same machine can be easily reconfigured to be a motor or generator if appropriate field excitation is available, since the DC machine has two fields termed field and armature. The field is usually on the stator side and the armature is on the rotor side (opposite or inside-out compared to AC machines). Field excitation can be provided by permanent magnets or a winding (coil)~~, and~~ . When current is applied to the armature or rotor coil, it passes from the DC source to the coil through brushes that are stationary and slip rings mounted on the rotating rotor touching the brushes. When~~ith~~ the rotor armature coil is a current-carrying loop and is exposed to an external field from the stator or field magnet, a force is exerted on the loop. Since the loop is "hanging" on both sides of the motor using bearings, the force will produce a torque that will rotate the rotor's shaft rather than move it in any other direction. This rotation causes the magnetic fields to align but at the same time, slip rings switch sides on the brushes, or "commute", and this is what is known as the commutation process. When this commutation occurs, current flow in the rotor coil is reversed and magnetic fields oppose each other again, causing further torque in the same direction of rotation. This process continues and the rotor shaft spins providing motor action. In generator operation, mechanical rotation is provided to the rotor shaft and current flows out of the rotor after it is induced due to a moving coil under a magnetic field.

T~~t~~he machines discussed in this experiment ~~are done~~have ~~with~~ a field winding rather than permanent magnets. A commutation process that is critical in DC machine operation uses slip rings and brushes to transfer energy from the rotor (armature) to the outside world since the rotor is spinning and having spinning wires would twist and break them. However, these brushes and slip rings ~~are of~~have major reliability drawbacks as they require regular maintenance, brush replacement, cleaning, and may cause sparking. This has led to replacement of most DC machines by AC machines that do not have these issues, and remaining DC machines mostly have permanent magnet field excitation, such as in toys and simple low power tools. AC machines termed brushless DC machines (or BLDCs) are AC machines that utilize a DC source and power electronic inverter to get AC voltages out of the inverter.

Principles

Four main configurations of DC machines exist: separately excited, shunt, series, and compound. These configurations are classified based on the location of the field excitation, where the field is one of the magnetic fields necessary to operate the machine as a motor or generator. Since the field winding is powered by a DC source, that source can be the same as the one powering the

Commented [AM1]: Give an introduction to the DC motor. How does it work? How does it differ from the AC motor? We will be introducing the instrument before discussing its characterization.

Ali: See the added paragraph to the left.

Commented [AM2]: We will be illustrating and animating the construction of a DC motor and starting with the basics of the machine. So we still need to cover the basics of *how it works*. Please go into more detail about how armature rotation is achieved from the magnetic field induced by the stator. You don't need to go into electromagnetics and the Lorentz Law, but we need to discuss *how* the rotation is achieved. What are the simple components of the motor that make it work? What is a commutator ring, why do you need many armature loops? It can be very brief, but it needs to discuss the very simple operation- we will likely begin the video with something like this figure to introduce the concept: http://roncalliphysics.wikispaces.com/file/view/dcmcur.gif/239414229/462x359/dcmcur.gif

Ali: See edits. The figure you have is good.

Commented [AM3]: These need to be briefly introduced. What is the key difference between each? What effect does each configuration have on torque speed? Which is more greatly affected by load? When would you use each configuration?

Ali: Configurations have been introduced. It is not practical to introduce all differences here as this could be a textbook chapter, but I think the introduction I added here is sufficient.

AKM: Yes, this introduction is helpful and sufficient.

DC motor's armature, or can be separate. When separate, the machine is termed "separately excited," and when not, the location of the field winding in the motor's circuit determines what type of configuration it is. If the field winding is placed in parallel with the armature winding to see the same voltage source powering the armature, the machine is in the parallel or shunt configuration. If the field winding is in series with the armature winding so they have the same current flow, the machine is in the series configuration. If both windings are available, i.e. shunt and series windings are used, then the machine is in the compound configuration. The separately excited configuration is independent from the armature and can be regulated to support various load through automatic control. However, shunt, series, and compound configurations draw current from the same armature source and are therefore affected by the load and armature voltage variations.

With no field excitation, residual magnetism due to the residual magnetic field (λ_R) in the machine acts as a source for minor field excitation. This can be expressed as an additional term in the back e.m.f. (E_A) equation $\lambda_R\omega$ which is added to $KI_F\omega$ where ω is the mechanical speed of the machine.. For a compound DC machine, E_A is thus,

$$E_A = K_{sh}I_{Fsh}\omega + K_{se}I_{Fse}\omega + \lambda_R\omega, \qquad \text{(Equation 1)}$$

where *se* stands for series, *sh* stands for shunt, and *K* terms are field constants that relate field current and mechanical speed to the back e.m.f.. Remember that *K* values are constant until a saturation limit is reached, after which E_A saturates to a certain value. Ideally, λ_R is assumed to be zero, but this is not realistic. In order to determine λ_R, a DC machine is run as a generator without shunt or series excitation and at no load. Thus, the terminal voltage measured V_A=E_A. If ω is measured, λ_R can be determined. E_A is a characteristic voltage of DC machines, a voltage that counters the armature voltage to limit the current into the machine. In motor operation, the E_A is less than the armature voltage and the higher E_A leads to less armature current draw. It is dependent on the shaft speed as shown in Equation 1, and therefore having a higher E_A causes higher speed operation. In generator applications, E_A is the induced voltage from rotating one magnetic field on the armature vs. the field.

For a shunt machine, Equation 1 still holds, but I_{Fse} is set to zero; for a series machine, Equation 1 still holds, but I_{Fsh} is set to zero. Compound machines have both shunt and series connected and can be in long- or short-form. When both fields exist, their effect can add up or oppose each other as seen by the armature, and these configurations are termed cumulative or differential. These configurations can be achieved by varying the location of the shunt field before or after the series field, and by having the field currents enter or leave their respective dots. **Figures 1-4** show all four configurations.

The goal of this experiment is to compare current, voltage and load relationships in series and shunt configured DC motors. Since only one high power DC power supply is available in this demonstration, separately excited operation is not covered. For shunt and series configurations, the prime mover of the DC generator is a synchronous motor that regulates its speed to 1800 RPM. Any time a DC current measurement is needed, such as I_A or I_{Fsh}, use the digital multi-meter in current mode (make sure the terminals on the multi-meter are in the current configuration).

Procedure

Commented [AM4]: Without first introducing the motor, and how it works- and how the four configurations differ- this equation is confusing to the viewer. Why does a DC motor produce back EMF? What effect does back EMF have on the rotor?

Ali: Done

Commented [AM5]: These variables have never been introduced to the viewer/reader. I'm not looking for detailed information about each variable, but we do need to introduce them.

Ali: I highlighted the definitions of these variables and added missing definitions.

Commented [AM6]: Have these figures been scanned out of a textbook? They may be copyrighted if so. Also, they are not web quality, and will need to be redrawn.

Commented [DM7]: Ali- we can redraw these, so long as they aren't copyrighted. I'm under the impression you created them, except for #4 and #8- is that correct?

Ali: If the images are scanned from a textbook then you can redraw them since they are standard circuits.

Commented [AM8]: Introduce the test you are running in the following protocol. What are we measuring? What are we looking for?

Ali: I do not quite understand the comment here, but the objective of the tests is to understand the voltage, current, load (torque/speed) relationships in shunt and series configurations.

AKM: I was looking for an introduction to the test, and what the overall goal of it is. Your comment is sufficient.

1. DC Tests

1.1 With the low-power DC power supply limited to 0.8 A, connect the supply terminals to the DC machine armature.

1.1.1 Record the supply's DC voltage and current readings.

1.1.2 Estimate the resistance of each winding.

1.1.3 Repeat for the other windings, shunt field and series field, one at a time.

1.1.4 Turn off and disconnect the low-power DC power supply.

1.2 Set the built-in field rheostat to maximum resistance and measure its resistance.

1.3 Set the series field rheostat (external) to the maximum resistance and measure its resistance.

2. Prime-Mover Setup and Residual Magnetism
The prime-mover in this experiment is the synchronous machine, which operates as a motor that spins the DC generator rotor (armature).

2.1 Make sure the three-phase disconnect switch, synchronous motor switch, and DC motor switch are all off.

2.1.1 Check that the VARIAC is at 0%.

2.1.2 Wire the VARIAC to the three-phase outlet, and connect the setup shown in **Figure 5**.

2.1.3 Check that the Start/Run switch is in the Start position.

2.2 Turn on the three-phase disconnect switch.

2.2.1 Turn on the high-voltage DC power supply.

2.2.2 Make sure all connections are clear from the supply terminals.

2.2.3 Press the V/I DIS button on the supply to display the voltage and current operating points. Adjust the voltage knob to 125 V.

2.2.4 *Do not press the start button*.

2.3 Press the "Start" button on the DC power supply panel.

2.3.1 Slowly increase the VARIAC output until V_{AC1} reads 120 V.

2.3.2 When the synchronous motor reaches a steady-state speed, flip the Start/Run switch into the Run position.

2.3.3 Measure and record the rotational speed using the strobe light and record V_A.

Commented [AM9]: How do you do this? Are you using the same strobe light technique as before?

Ali: Yes. You can mention it here if you wish.

2.4 Turn off the DC power supply and return the VARIAC to 0%.

2.4.1 Reset the Start/Run switch to Start.

2.4.2 Turn off the three-phase disconnect switch.

3. DC Shunt Generator Characterization

3.1 On the DC generator side, connect the shunt field in parallel with the armature field as shown in **Figure 6**.

3.1.1 Use the built-in rheostat for $R_{Fsh(ext)}$, and use the multi-meter as an ammeter to measure I_{Fsh}.

3.1.2 Keep S_1 open for a no-load test.

3.1.3 Keep $R_{Fsh(ext)}$ at maximum resistance.

3.2 Turn on the three-phase disconnect switch.

3.2.1 Press the "Start" button on the DC power supply panel.

3.3 Slowly increase the VARIAC output until V_{AC1} reads 120 V.

3.3.1 When the synchronous motor reaches a steady-state speed, flip the Start/Run switch into the Run position.

3.3.2 Measure the shaft speed.

3.3.3 Record V_A at this no-load condition on the DC generator side.

3.4 Reduce $R_{Fsh(ext)}$ until the voltage generated at V_A is around 150 V.

3.4.1 After that point, reduce $R_{Fsh(ext)}$ in five almost-equal steps until the minimum resistance is reached.

3.4.2 For each step, measure V_A and $\boldsymbol{I_{Fsh}}$.

3.5 Leave $R_{Fsh(ext)}$ at its minimum value.

3.5.1 Turn off the DC power supply.

3.5.2 Reduce the VARIAC output to 0%.

3.5.3 Move the ammeter from measuring I_{Fsh} to measure I_A.

3.5.4 Restart the setup as described earlier.

3.6 Set R_L to 300 Ω, and turn on S_1. Measure V_A and I_A.

3.6.1 Turn off S1, set R_L to 200 Ω, then turn on S_1. Measure V_A, and I_A.

3.6.2 Turn off S1, set R_L to 100 Ω, then turn on S_1. Measure V_A, and I_A.

3.6.3 Turn off the DC power supply and set the VARIAC output to 0%.

3.6.4 Keep the synchronous generator side of the setup intact.

3.6.5 Disconnect the DC generator connections.

3.7 Reset the Start/Run switch to Start.

3.8 Turn off the three-phase disconnect switch.

4. DC Series Generator Characterization

4.1 On the DC generator side, connect the series field in series with the armature field as shown in **Figure 7**.

4.1.1 Use the external rheostat for $R_{Fse(ext)}$.

4.1.2 Use the built-in rheostat as R_L and have it at maximum resistance.

4.1.3 Keep S_1 open for a no-load test.

4.1.4 Keep $R_{Fse(ext)}$ at maximum resistance.

4.2 Turn on the three-phase disconnect switch.

4.2.1 Press the “Start” button on the DC power supply panel.

4.3 Slowly increase the VARIAC output until V_{AC1} reads 120 V.

4.3.1 When the synchronous motor reaches a steady-state speed, flip the Start/Run switch into the Run position.

4.3.2 Measure V_A at this no-load condition on the DC generator side.

4.4 Turn on S_1 and reduce $R_{Fse(ext)}$ as needed to see non-zero V_A.

4.4.1 Vary R_L in five almost-equal steps until its 50% setting is reached, set to 300 Ω, and turn on S_1. Measure the speed, V_A, and I_A.

4.4.2 Turn off S1, set R_L to 200 Ω, then turn on S_1. Measure the speed, V_A, and I_A.

4.4.3 Turn off S1, set R_L to 100 Ω, then turn on S_1. Measure the speed, V_A, and I_A.

Commented [AM10]: Will you be providing representative data? What do you expect from each test? What difference do you see between the shunt and series configurations?

Ali: I do not have numerical values now but these will be provided during filming. IF needed, you can add the following observation where you find suitable:

"I_A is expected to increase with lower load resistance, i.e. higher loads, as the impedance seen from the back e.m.f. across the armature and field windings has dropped and more current draw is expected. V_A may increase then drop depending on the load since the back e.m.f. is not constant—when more current is drawn by the load, the series field current which is the same as the armature current in this case would increase and thus E_A would increase; however, this increase in current leads to increase of voltage drop across the armature and series windings leading to a decrease in V_A. In steady state, the load resistance value compared to the field and armature resistances, and the variation of E_A will determine how much I_A and E_A will increase or decrease."

4.5 Turn off the DC power supply.

4.5.1 Set the VARIAC output to 0%.

4.5.2 Keep the synchronous generator side of the setup intact.

4.5.3 Disconnect the DC generator connections.

4.5.4 Reset the Start/Run switch to Start.

4.6 Turn off the three-phase disconnect switch.

4.7 Disassemble all wires and meters.

Representative Results

Series windings typically carry high current rated at the machine's rated armature current, since both series and armature windings are in series. Therefore, series windings are expected to be on the order of a mΩ to a few Ω. Shunt windings on the other hand should draw minimum current from the source which power them along with the machine's armature, and therefore, have large resistance values of tens to hundreds or even thousands of Ω.

The residual λ_R can be estimated by measuring the armature voltage at no load. Since this a no-load condition, the back e.m.f. and armature voltage are the same, and the back e.m.f. (E_A) is a function of λ_R such that $E_A=I_f\,\lambda_R\omega_m$ where I_f is the field current and ω_m is the mechanical speed.

Each type of machine has its own voltage-current or torque-speed curve (**Figure 8**). The advantage of shunt generators is that they can provide voltage without having any load up to full load, while series generators are characterized by not being able to provide any voltage unless there is some load.

Applications

DC machines are significantly less common than they used to be before the invention of AC induction and synchronous machines. They remain common in simple low power applications such as toys, small robots, and legacy equipment. Permanent magnet DC machines, which use abundant non-rare-earth magnets, are more common than their shunt and series counter parts due to simpler excitation, especially in low cost and low complexity applications.

Legend

Figure 1: A schematic of a cumulative long compound configuration.

Figure 2: A schematic of a cumulative short compound configuration.

Figure 3: A schematic of a differential long compound configuration.

Figure 4: A schematic of a differential short compound configuration.
Source for **Figures 1-4**: 11.1-11.4: Stephen J. Chapman, "Electric Machinery Fundamentals," 5th edition, McGraw Hill, New York, NY, USA, 2012.

Figure 5: A schematic of how to setup the prime-mover.

Figure 6: A schematic of the shunt DC generator setup.

Figure 7: A schematic of the series DC generator setup.

Figure 8: A graph showing a few examples of different torque-speed curves.
Source: http://www.electrical4u.com/images/performance-curves-of-dc-ge.gif

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