UNIT V
TESTING OF DC MACHINES

5.1 Introduction

In the previous sections we have learnt about the principle of operation of d.c. generators and motors, (starting and speed control of d.c motor). Motors convert *electrical* power (input power) into *mechanical* power (output power) while generators convert *mechanical* power (input power) into *electrical* power (output power). Whole of the input power can not be converted into the output power in a practical machine due to various losses that take place within the machine. Efficiency η being the ratio of output power to input power, is always less than 1 (or 100 %). Designer of course will try to make η as large as possible. Order of efficiency of rotating d.c machine is about 80 % to 85 %. It is therefore important to identify the losses which make efficiency poor.

In this lesson we shall first identify the losses and then try to estimate them to get an idea of efficiency of a given d.c machine.

5.2 Major losses

Take the case of a loaded d.c motor. There will be copper losses ($I_a^2 r_a$ and $I^2_f R_f = VI_f$) in armature and field circuit. The armature copper loss is variable and depends upon degree of loading of the machine. For a shunt machine, the field copper loss will be constant if field resistance is not varied. Recall that rotor body is made of iron with slots in which armature conductors are placed. Therefore when armature rotates in presence of field produced by stator field coil, eddy current and hysteresis losses are bound to occur on the rotor body made of iron. The sum of eddy current and hysteresis losses is called the *core* loss or *iron* loss. To reduce *core* loss, circular varnished and slotted laminations or *stamping* are used to fabricate the armature. The value of the core loss will depend on the strength of the field and the armature speed. Apart from these there will be power loss due to *friction* occurring at the bearing & shaft and air friction (windage loss) due to rotation of the armature. To summarise following major losses occur in a d.c machine.

7. Field copper loss: It is power loss in the field circuit and equal to $I_f^2 R_f = VI_f$. During the course of loading if field circuit resistance is not varied, field copper loss remains constant.
8. Armature copper loss: It is power loss in the armature circuit and equal to $I_a^2 R_a$. Since the value of armature current is decided by the load, armature copper loss becomes a function of time.
9. Core loss: It is the sum of eddy current and hysteresis loss and occurs mainly in the rotor iron parts of armature. With constant field current and if speed does not vary much with loading, core loss may be assumed to be constant.
10. Mechanical loss: It is the sum of bearing friction loss and the windage loss (friction loss due to armature rotation in air). For practically constant speed operation, this loss too, may be assumed to be constant.

Apart from the major losses as enumerated above there may be a small amount loss called *stray* loss occur in a machine. Stray losses are difficult to account. Power flow diagram of a d.c motor is shown in figure 40.1. A portion of the input power is consumed by the field circuit as field copper loss. The remaining power is the power which goes to the armature; a portion of which is lost as core loss in the armature core and armature copper loss. Remaining power is the gross mechanical power developed of which a portion will be lost as friction and remaining power will be the net mechanical power developed. Obviously efficiency of the motor will be given by:

$$\eta = \frac{P_{net\ mech}}{P_{in}}$$

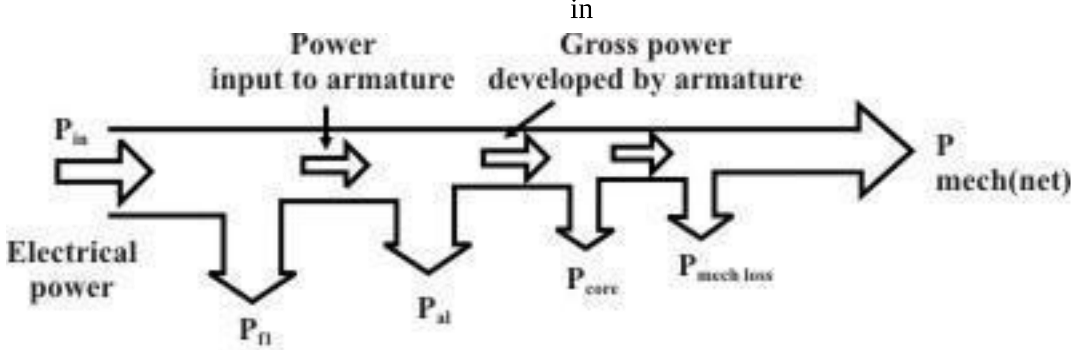


Fig. 40.1: Power flow diagram of a D.C. motor

Similar power flow diagram of a d.c generator can be drawn to show various losses and input, output power (figure 40.2).

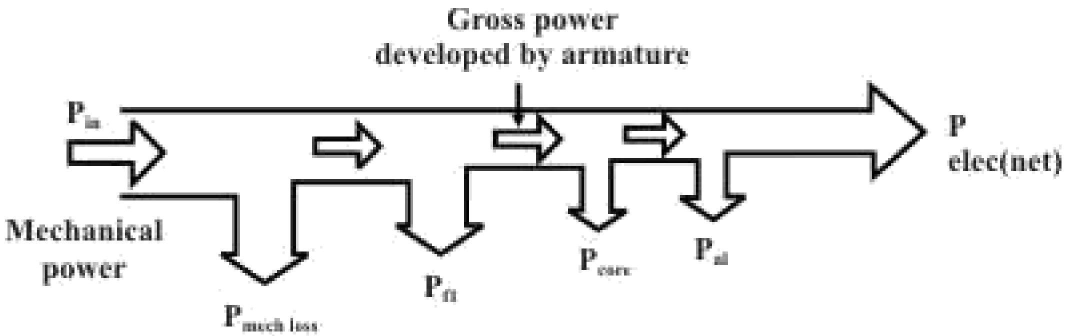


Fig. 40.2: Power flow diagram of a D.C. generator

It is important to note that the name plate kW (or hp) rating of a d.c machine always corresponds to the net **output** at rated condition for both generator and motor.

5.3 Swinburne’s Test

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same.

In this test, the motor is run at rated speed under *no load* condition at rated voltage. The current drawn from the supply I_{L0} and the field current I_f are recorded (figure 40.3). Now we note that:

Input power to the motor, P_{in}
Cu loss in the field circuit P_{fl}
Power input to the armature,

4. VI_{L0}
5. VI_f
6. $VI_{L0} - VI_f$
7. $V(I_{L0} - I_f)$
8. VI_{a0}

Cu loss in the armature circuit $= I_{a0}^2 r_a$

Gross power developed by armature $= VI_{a0} - I_{a0}^2 r_a$

$= (V - I_{a0} r_a) I_{a0}$

7. $b_0 I_{a0}$

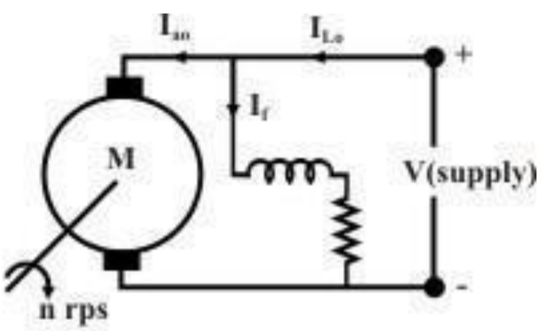


Fig. 40.3: Motor under no load

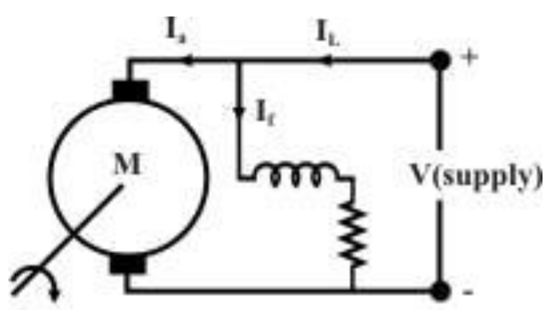


Fig. 40.4: Motor Loaded

Since the motor is operating under no load condition, net mechanical output power is zero. Hence the gross power developed by the armature must supply the core loss and friction & windage losses of the motor. Therefore,

$$P_{core} + P_{friction} = (V - I_{a0} r_a) I_{a0} = E_{b0} I_{a0}$$

Since, both P_{core} and $P_{friction}$ for a shunt motor remains practically constant from no load to full load, the sum of these losses is called constant rotational loss i.e.,

constant rotational loss, $P_{rot} = P_{core} + P_{friction}$

In the Swinburne's test, the constant rotational loss comprising of core and friction loss is estimated from the above equation.

After knowing the value of P_{rot} from the Swinburne's test, we can fairly estimate the efficiency of the motor at any loading condition. Let the motor be loaded such that new current drawn from the supply is I_L and the new armature current is I_a as shown in figure 40.4. To estimate the efficiency of the loaded motor we proceed as follows:

Input power to the motor, P_{in} = VI_L

Cu loss in the field circuit P_{fl} = VI_f

Power input to the armature, = $VI_L - VI_f$

= $V(I_L - I_f)$

= VI_a

Cu loss in the armature circuit = $I_a r_a$

Gross power developed by armature = $VI_a - I_a r_a$

= $(V - I_a r_a) I_a$

= $E_b I_a$

Net mechanical output power, $P_{net\,mech}$ = $E_b I_a - P_{rot}$

$\therefore$ efficiency of the loaded motor, η = $\dfrac{E_b I_a - P_{rot}}{VI_L}$

= $\dfrac{P_{net\,mech}}{P_{in}}$

The estimated value of P_{rot} obtained from Swinburne's test can also be used to estimate the efficiency of the shunt machine operating as a generator. In figure 40.5 is shown to deliver a load current I_L to a load resistor R_L. In this case output power being known, it is easier to add the losses to estimate the input mechanical power.

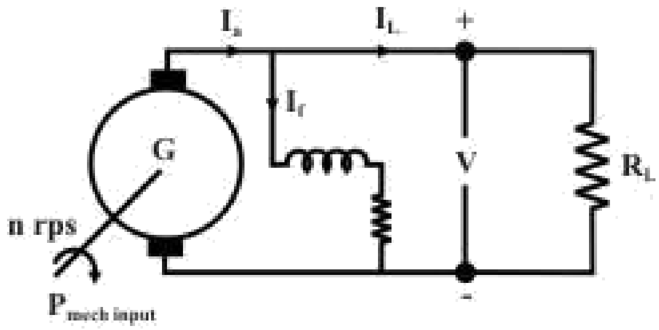


Fig. 40.5: Loaded d.c. generator

Output power of the generator, P_{out} 9. VI_L

Cu loss in the field circuit P_{fl} 10. VI_f

Output power of the armature, 11. $VI_L + VI_f$ 12. VI_a

Mechanical input power, $P_{in\,mech}$ 13. $VI_a + I_a^2 r_a + P_{rot}$

∴ Efficiency of the generator, η (viii) $\frac{VI_L}{P_{in\,mech}}$

$$= \frac{VI_L}{VI_a + I_a^2 r_a + P_{arot}}$$

The biggest advantage of Swinburne's test is that the shunt machine is to be run as motor under *no load* condition requiring little power to be drawn from the supply; based on the no load reading, efficiency can be predicted for any load current. However, this test is not sufficient if we want to know more about its performance (effect of armature reaction, temperature rise, commutation etc.) when it is actually loaded. Obviously the solution is to load the machine by connecting mechanical load directly on the shaft for motor or by connecting loading rheostat across the terminals for generator operation. This although sounds simple but difficult to implement in the laboratory for high rating machines (say above 20 kW), Thus the laboratory must have proper supply to deliver such a large power corresponding to the rating of the machine. Secondly, one should have loads to absorb this power.

5.4 *Hopkinson's test*

This as an elegant method of testing d.c machines. Here it will be shown that while power drawn from the supply only corresponds to no load losses of the machines, the armature physically carries any amount of current (which can be controlled with ease). Such a scenario can be created using two similar mechanically coupled shunt machines. Electrically these two machines are eventually connected in parallel and controlled in such a way that one machine acts as a generator and the other as motor. In other words two similar machines are required to carry out this testing which is not a bad proposition for manufacturer as large numbers of similar machines are manufactured.

Procedure

Connect the two similar (same rating) coupled machines as shown in figure 40.6. With switch S opened, the first machine is run as a shunt motor at rated speed. It may be noted that the second machine is operating as a separately excited generator because its field winding is excited and it is driven by the first machine. Now the question is what will be the reading of the voltmeter connected across the opened switch S? The reading may be (i) either close to twice supply voltage or (ii) small voltage. In fact the voltmeter practically reads the difference of the induced voltages in the armature of the machines. The upper armature terminal of the generator may have either + ve or negative polarity. If it happens to be +ve, then voltmeter reading will be small otherwise it will be almost double the supply voltage.

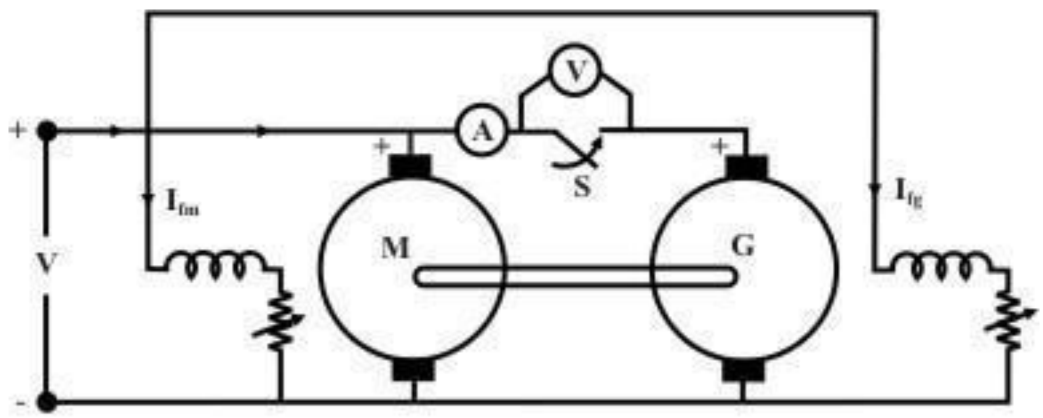


Fig. 40.6: Hopkinson's test: machines before paralleling

Since the goal is to connect the two machines in parallel, we must first ensure voltmeter reading is small. In case we find voltmeter reading is high, we should switch off the supply, reverse the armature connection of the generator and start afresh. Now voltmeter is found to read small although time is still not ripe enough to close S for paralleling the machines. Any attempt to close the switch may result into large circulating current as the armature resistances are small.
Now by adjusting the field current I_{fg} of the generator the voltmeter reading may be adjusted to zero ($E_g \approx E_b$) and S is now closed. Both the machines are now connected in parallel as shown in figure 40.7.

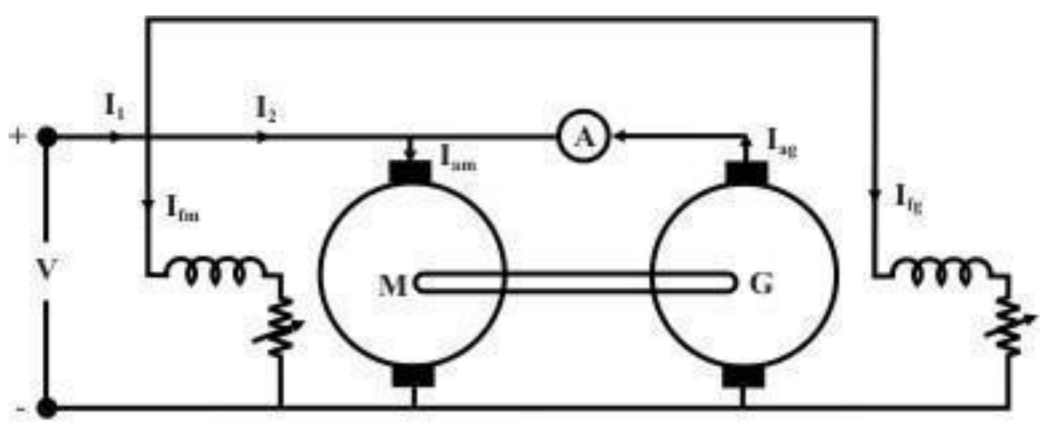


Fig. 40.7: Hopkinson's test: machines paralled

Loading the machines

After the machines are successfully connected in parallel, we go for loading the machines i.e., increasing the armature currents. Just after paralleling the ammeter reading A will be close to zero as $E_g \approx E_b$. Now if I_{fg} is increased (by decreasing R_{fg}), then E_g becomes greater than E_b and both I_{ag} and I_{am} increase, Thus by increasing field current of generator (alternatively decreasing field current of motor) one can make $E_g > E_b$ so as to make the second machine act as generator and first machine as motor. In practice, it is also required to control the field current of the motor I_{fm} to maintain speed constant at rated value. The interesting point to be noted here is that I_{ag} and I_{am} do not reflect in the supply side line. Thus current drawn from supply remains small (corresponding to losses of both the machines). The loading is sustained by the output power of the generator running the motor and vice versa. The machines can be loaded to full load current without the need of any loading arrangement.

Calculation of efficiency

Let field currents of the machines be are so adjusted that the second machine is acting as generator with armature current I_{ag} and the first machine is acting as motor with armature current I_{am} as shown in figure 40.7. Also let us assume the current drawn from the supply be I_1.
Total power drawn from supply is VI_1 which goes to supply all the losses (namely Cu losses in armature & field and rotational losses) of both the machines,
Now:

$$
\begin{aligned}
\text{Power drawn from supply} &= VI_1 \\
\text{Field Cu loss for motor} &= VI_{fm} \\
\text{Field Cu loss for generator} &= VI_{fg} \\
\text{Armature Cu loss for motor} &= I_{am}^2 r_{am} \\
\text{Armature Cu loss for generator} &= I_{ag}^2 r_{ag} \\
\therefore \text{Rotational losses of both the machines} &= VI_1 - (VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag}) \qquad (40.1)
\end{aligned}
$$

Since speed of both the machines are same, it is reasonable to assume the rotational losses of both the machines are equal; which is strictly not correct as the field current of the generator will be a bit more than the field current of the motor, Thus,

$$\text{Rotational loss of each machine, } P_{rot} = \frac{VI_1 - (VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag})}{2}$$

Once P_{rot} is estimated for each machine we can proceed to calculate the efficiency of the machines as follows,

Efficiency of the motor

As pointed out earlier, for efficiency calculation of motor, first calculate the input power and then subtract the losses to get the output mechanical power as shown below, Total power input to the motor = power input to its field + power input to its armature

$$P_{inm} = VI_{fm} + VI_{am}$$

Losses of the motor = $VI_{fm} + I_{am}^2 r_{am} + P_{rot}$

Net mechanical output power $P_{outm} = P_{inm} - (VI_{fm} + I_{am}^2 r_{am} + P_{rot})$

$$\therefore \eta_m = \frac{P_{outm}}{P_{inm}}$$

Efficiency of the generator

For generator start with output power of the generator and then add the losses to get the input mechanical power and hence efficiency as shown below,

Output power of the generator, $P_{outg} = VI_{ag}$

Losses of the generator = $VI_{fg} + I_{ag}^2 r_{ag} + P_{rot}$

Input power to the generator, $P_{ing} = P_{outg} + (VI_{fg} + I_{ag}^2 r_{ag} + P_{rot})$

$$\therefore \eta_g = \frac{P_{outg}}{P_{ing}}$$

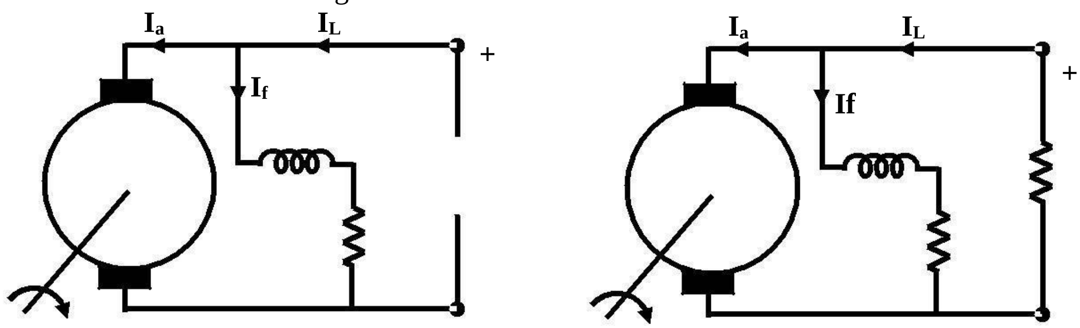
5.5 Condition for maximum efficiency

We have seen that in a transformer, maximum efficiency occurs when copper loss = core loss, where, copper loss is the variable loss and is a function of loading while the core loss is practically constant independent of degree of loading. This condition can be stated in a different way: maximum efficiency occurs when the variable loss is equal to the constant loss of the transformer.

Here we shall see that similar condition also exists for obtaining maximum efficiency in a d.c shunt machine as well.

Maximum efficiency for motor mode

Let us consider a loaded shunt motor as shown in figure 40.8. The various currents along with their directions are also shown in the figure.



We assume that field current I_f remains constant during change of loading. Let,

P_{rot} = constant rotational loss

$V I_f$ = constant field copper loss

Constant loss $P_{const} = P_{rot} + V I_f$

Now, input power drawn from supply $= V I_L$

Power loss in the armature, $= I_a^2 r_a$

Net mechanical output power $= VI_L - I_a^2 r_a - (VI_f + P_{rot})$

$$= VI_L - I_a^2 r_a - P_{const}$$

so, efficiency at this load current $\eta_m = \dfrac{VI_L - I_a^2 r_a - P_{const}}{VI_L}$

Now the armature copper loss $I_a^2 r_a$ can be approximated to $I_L^2 r_a$ as $I_a \approx I_L$. This is because the order of field current may be 3 to 5% of the rated current. Except for very lightly loaded motor, this assumption is reasonably fair. Therefore replacing I_a by I_f in the above expression for efficiency η_m , we get,

$$\eta_m = \frac{VI_L - I_L^2 r_a - P_{const}}{VI_L}$$

$$= 1 - \frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}$$

$$\frac{d\eta_m}{dI_L} = 0$$

$$\text{or, } \frac{d}{dI_L}\left(\frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}\right) = 0$$

$$\text{or, } -\frac{r_a}{V} + \frac{P_{const}}{VI_L^2}$$

$\therefore$Condition for maximum efficiency is $I_a^2 r_a \approx I_L^2 r_a = P_{const}$

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So, the armature current at which efficiency becomes maximum is I_a

Thus, we get a simplified expression for motor efficiency η_m in terms of the variable current (which depends on degree of loading) I_L, current drawn from the supply. So to find out the condition for maximum efficiency, we have to differentiate η_m with respect to I_L and set it to zero as shown below.

Maximum efficiency for Generation mode

Similar derivation is given below for finding the condition for maximum efficiency in generator mode by referring to figure 40.9.

We assume that field current I_f remains constant during change of loading. Let,

$$\frac{d\eta_g}{dI_L} = 0$$

or, $$\frac{d}{dI_L}\left(\frac{VI_L}{VI_L + I_L^2 r_a + P_{const}}\right) = 0$$

∴Simplifying we get the condition as $I_L^2 r_a \approx I_a^2 r_a = P_{const}$

So, the armature current at which efficiency becomes maximum is $I_a = \sqrt{P_{const}/r_a}$

P_{rot} = constant rotational loss

$V I_f$ = constant field copper loss

Constant loss $P_{const} = P_{rot} + V I_f$

Net output power to load = $V I_L$

Power loss in the armature, = $I_a^2 r_a$

Mechanical input power = $VI_L + I_a^2 r_a + (VI_f + P_{rot})$

$= VI_L + I_a^2 r_a + P_{const}$

so, efficiency at this load current $\eta_g = \dfrac{VI_L}{VI_L + I_a^2 r_a + P_{const}}$

As we did in case of motor, the armature copper loss $I_a^2 r_a$ can be approximated to $I_L^2 r_a$ as $I_a \approx I_L$. So expression for η_g becomes,

$$\eta_g = \frac{VI_L}{VI_L + I_L^2 r_a + P_{const}}$$

Thus, we get a simplified expression for motor efficiency η_g in terms of the variable current (which depends on degree of loading) I_L, current delivered to the load. So to find out the condition for maximum efficiency, we have to differentiate η_g with respect to I_L and set it to zero as shown below.

Thus maximum efficiency both for motoring and generating are same in case of shunt machines. To state we can say at that armature current maximum efficiency will occur which will make variable loss = constant loss. Eventually this leads to the expression for armature current for maximum efficiency as $I_a = \sqrt{P_{const}/r_a}$.