Slip Power Recovery Schemes

Introduction

In a wound-field induction motor the slip rings allow easy recovery of the slip power which can be electronically controlled to control the speed of the motor.

The oldest and simplest technique to invoke this slip-power recovery induction motor speed control is to mechanically vary the rotor resistance.

Introduction (cont'd)

Slip-power recovery drives are used in the following applications:

- Large-capacity pumps and fan drives
- Variable-speed wind energy systems
- Shipboard VSCF (variable-speed/constant frequency) systems
- Variable speed hydro-pumps/generators
- Utility system flywheel energy storage systems

Speed Control by Rotor Rheostat

Recall that the torque-slip equation for an induction motor is given by:

$$T_e = 3\left(\frac{P}{2}\right)\frac{R_r}{s\omega_e}\cdot\frac{V_s^2}{\left(R_s + R_r / s\right)^2 + \omega_e^2 (L_{ls} + L_{lr})^2}$$

From this equation it is clear that the torque-slip curves are dependent on the rotor resistance R_r. The curves for different rotor resistances are shown on the next slide for four different rotor resistances (R_1-R_4) with $R_4 > R_3 > R_2 > R_1$.

Speed Control by Rotor Rheostat (cont'd)

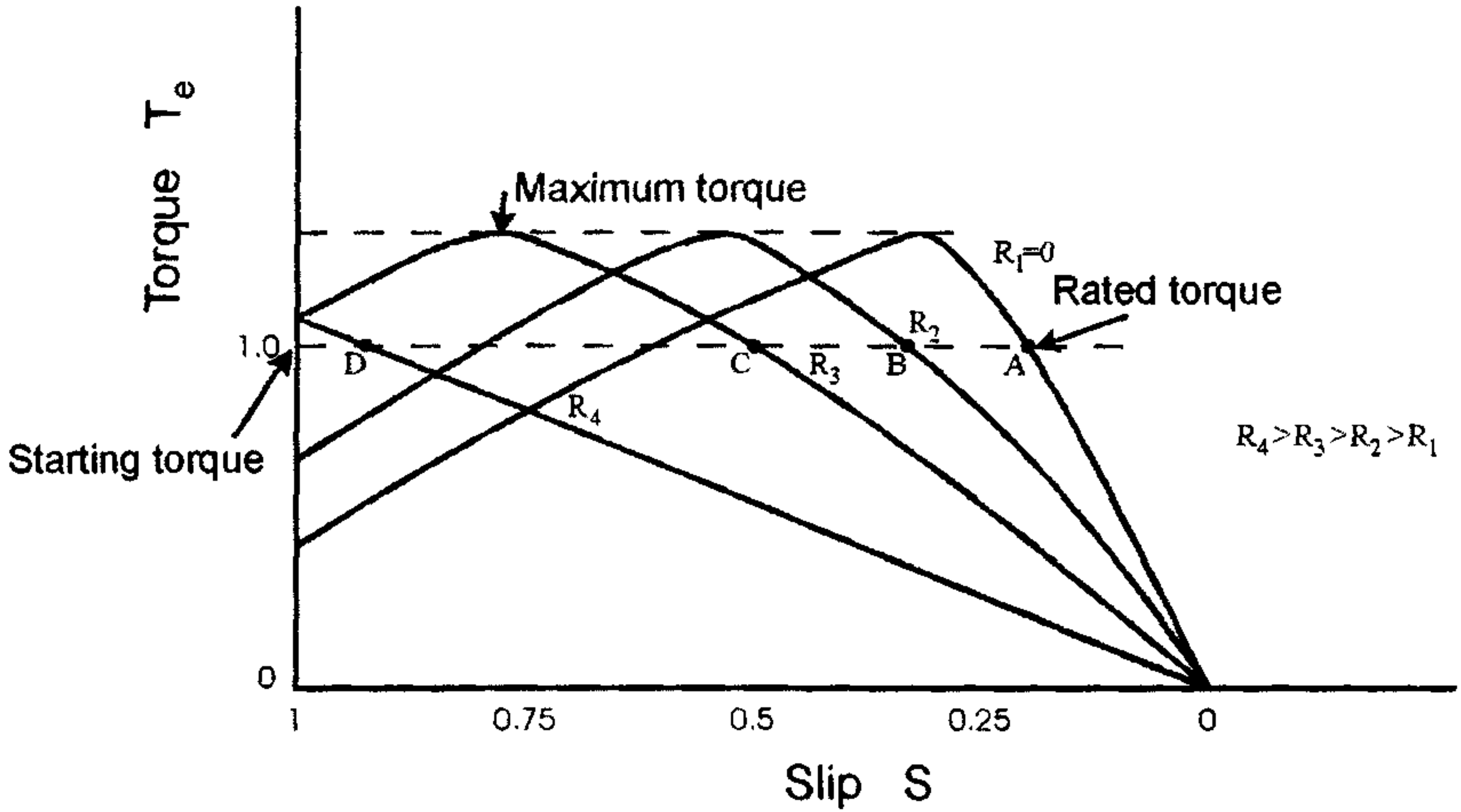


Figure 7.2 Torque-slip curves of motor with variable rotor resistance

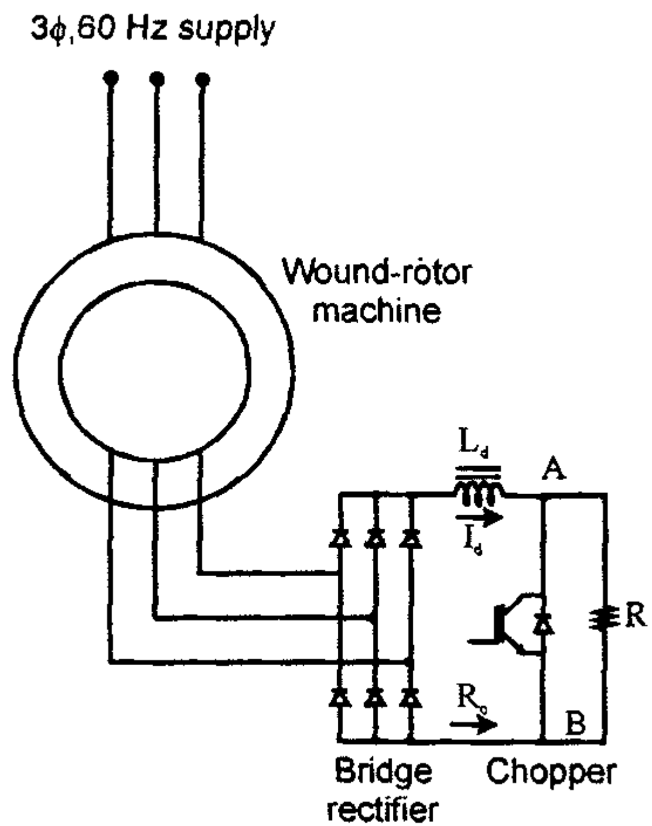
Speed Control by Rotor Rheostat (cont'd)

With R_1=0, i.e. slip rings shorted, speed is determined by rated load torque (pt. A). As R_r increases, curve becomes flatter leading to lower speed until speed becomes zero for $R_r > R_4$.

Although this approach is very simple, it is also very inefficient because the slip energy is wasted in the rotor resistance.

Speed Control by Rotor Rheostat (cont'd)

An electronic chopper implementation is also possible as shown below but is equally inefficient.



Static Kramer Drive

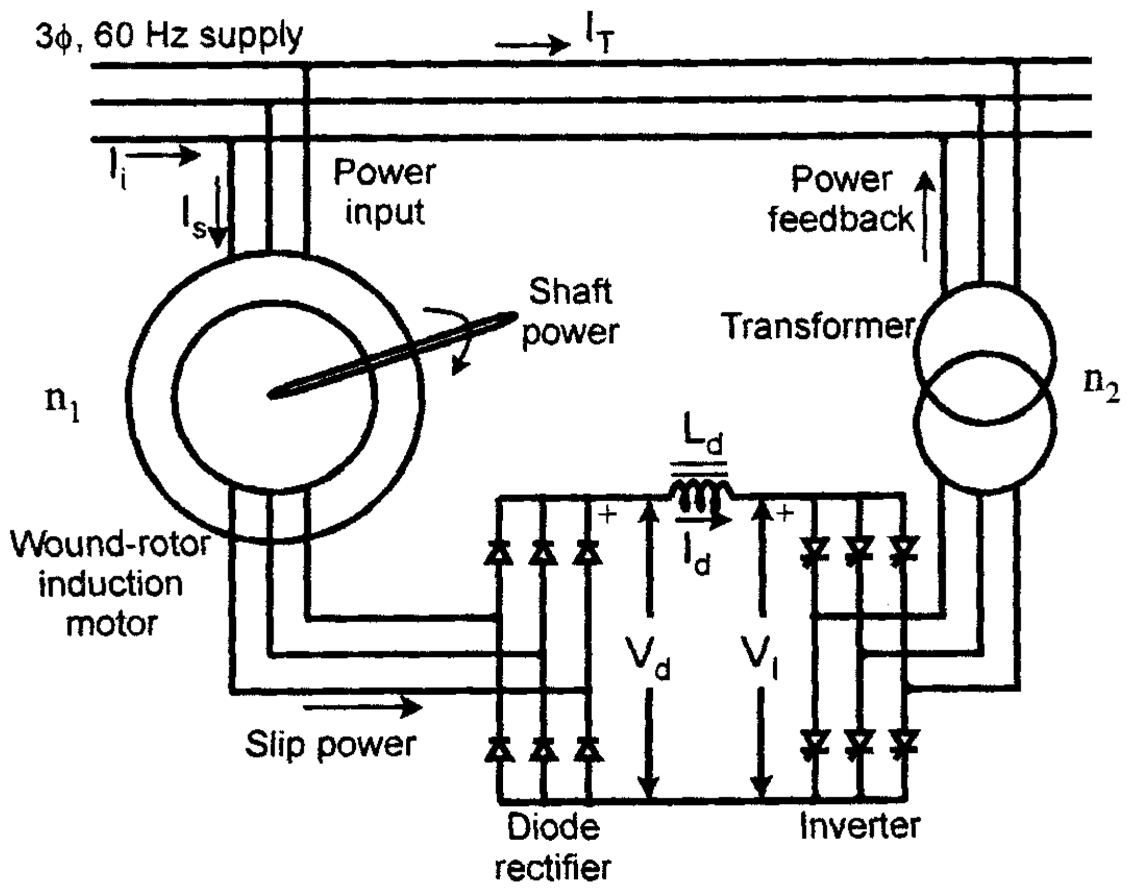
Instead of wasting the slip power in the rotor circuit resistance, a better approach is to convert it to ac line power and return it back to the line. Two types of converter provide this approach:

1) Static Kramer Drive - only allows operation at sub-synchronous speed.

2) Static Scherbius Drive - allows operation above and below synchronous speed.

Static Kramer Drive (cont'd)

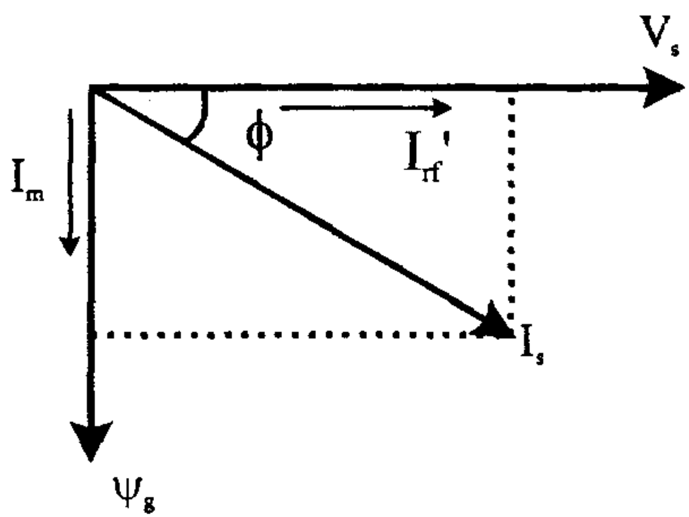
A schematic of the static Kramer drive is shown below:



Static Kramer Drive (cont'd)

The machine air gap flux is created by the stator supply and is essentially constant. The rotor current is ideally a 6-step wave in phase with the rotor voltage.

The motor fundamental phasor diagram referred to the stator is as shown below:



V_s = stator phase voltage, I_s=stator current, I_{rf}' = fundamental rotor current referred to the stator, ψ_g = air gap flux, I_m=magnetizing current, and ϕ=PF angle.

Static Kramer Drive (cont'd)

The voltage V_d is proportional to slip, s and the current I_d is proportional to torque. At a particular speed, the inverter's firing angle can be decreased to decrease the voltage V_I. This will increase I_d and thus the torque. A simplified torque-speed expression for this implementation is developed next.

Static Kramer Drive (cont'd)

Voltage V_d (neglecting stator and rotor voltage drops) is given by:

$$V_d = \frac{1.35 s V_L}{n_1}$$

where s=per unit slip, V_L= stator line voltage and n_1=stator-to-rotor turns ratio. The inverter dc voltage V_I is given by:

$$V_I = \frac{1.35 V_L \left|\cos\alpha\right|}{n_2}$$

where n_2=transformer turns ratio (line side to inverter side) and α=inverter firing angle.

Static Kramer Drive (cont'd)

For inverter operation, $\pi/2<\alpha<\pi$. In steady state $V_d=V_I$ (neglecting ESR loss in inductor)

=> $$s=\frac{n_1}{n_2}\left|\cos\alpha\right|$$

The rotor speed ω_r is given by:

$$\omega_r=(1-s)\omega_e=\left(1-\frac{n_1}{n_2}\left|\cos\alpha\right|\right)\omega_e = \left(1-\left|\cos\alpha\right|\right)\omega_e \quad \text{if } n_1=n_2$$

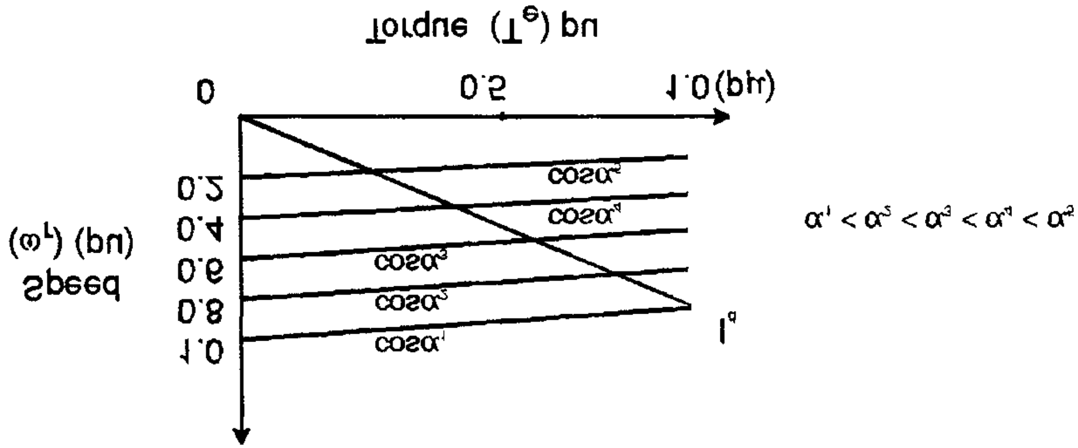
Thus rotor speed can be controlled by controlling inverter firing angle, α. At $\alpha=\pi$, $\omega_r=0$ and at $\alpha=\pi/2$, $\omega_r=\omega_e$.

Static Kramer Drive (cont'd)

It can be shown (see text) that the torque may be expressed as:

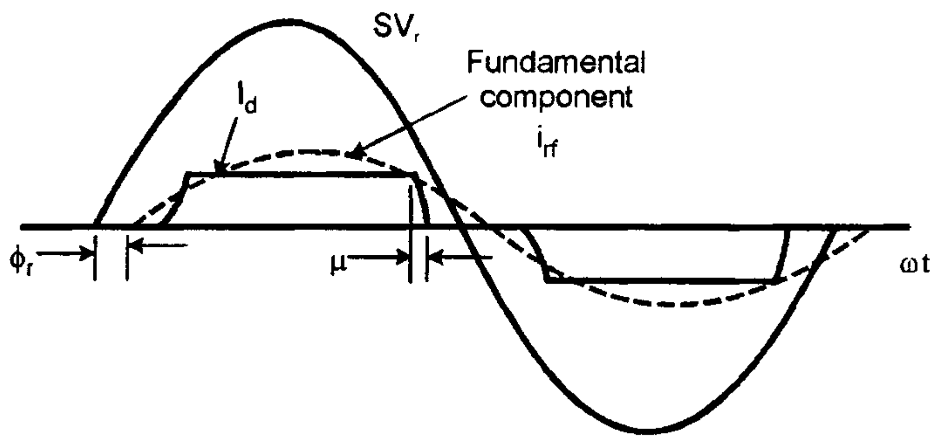
$$T_e = \left(\frac{P}{2}\right)\frac{1.35V_L}{\omega_e n_1} I_d$$

The below figure shows the torque-speed curves at different inverter angles.



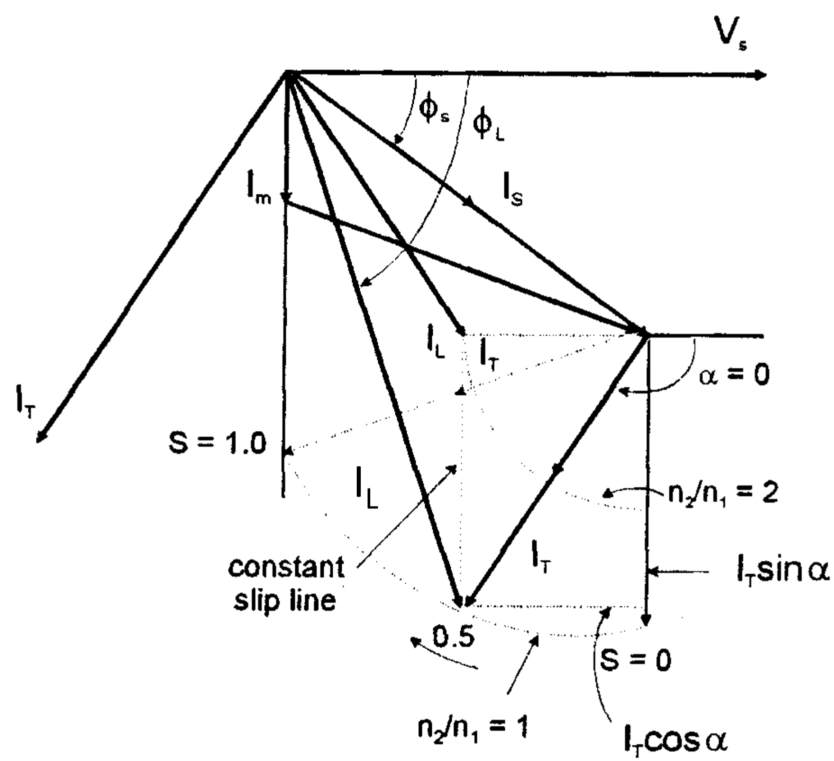
Static Kramer Drive (cont'd)

The fundamental component of the rotor current lags the rotor phase voltage by ϕ_r because of a commutation overlap angle μ (see figure below). At near zero slip when rotor voltage is small, this overlap angle can exceed $\pi/3$ resulting in shorting of the upper and lower diodes.



Static Kramer Drive (cont'd)

The phasor diagram for a static Kramer drive at rated voltage is shown below:



<u>Note</u>: All phasors are referred to stator.

Static Kramer Drive (cont'd)

On the inverter side, reactive power is drawn by the line -> reduction in power factor ($\phi_L > \phi_s$). The inverter line current phasor is I_T. The figure shows I_T at s=0.5 for $n_1=n_2$. The real component $I_T\cos\alpha$ opposes the real component of the stator current but the reactive component $I_T\sin\alpha$ adds to the stator magnetizing current. The total line current I_L is the phasor sum of I_T and I_S. With constant torque, the magnitude of I_T is constant but as slip varies, the phasor I_T rotates from $\alpha=90°$ at s=0 to $\alpha=160°$ at s=1.

Static Kramer Drive (cont'd)

At zero speed (s=1) the motor acts as a transformer and all the real power is transferred back to the line (neglecting losses). The motor and inverter only consume reactive power.

At synchronous speed (s=0) the power factor is the lowest and increases as slip increases. The PF can be improved close to synchronous speed by using a step-down transformer. The inverter line current is reduced by the transformer turns ratio -> reduced PF.

Static Kramer Drive (cont’d)

A further advantage of the step-down transformer is that since it reduces the inverter voltage by the turns ratio, the device power ratings for the switching devices in the inverter may also be reduced.

A starting method for a static Kramer drive is shown on the next slide.

Static Kramer Drive (cont'd)

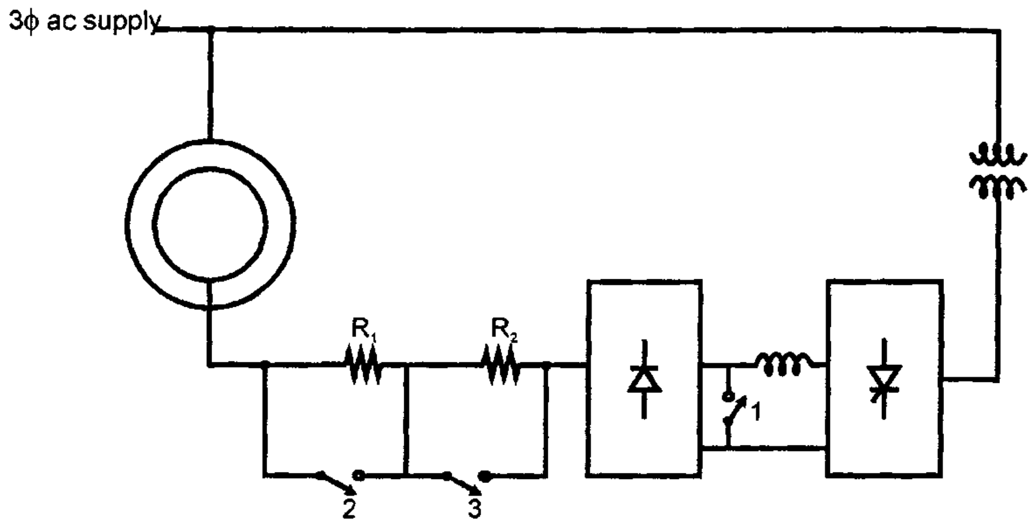


Figure 7.9 Motor starting method

The motor is started with switch 1 closed and switches 2 and 3 open. As the motor builds up speed, switches 2 and 3 are sequentially closed until desired s_{max} value is reached after which switch 1 is opened and the drive controller takes over.

AC Equivalent Circuit of Static Kramer Drive

Use an ac equivalent circuit to analyze the performance of the static Kramer drive. The slip-power is partly lost in the dc link resistance and partly transferred back to the line. The two components are:

$P_l = I_d^2 R_d$ and

$$P_f = \frac{1.35 V_L I_d}{n_2} \left|\cos\alpha\right|$$

Thus the rotor power per phase is given by:

$$P' = P_l' + P_f' = \frac{1}{3}\left(I_d^2 R_d + \frac{1.35 V_L I_d}{n_2} \left|\cos\alpha\right| \right)$$

AC Equivalent Circuit of Static Kramer Drive (cont'd)

Therefore, the motor air gap power per phase is given by:

$$P_g^{'} = I_r^2 R_r + P' + P_m^{'}$$

where I_r=rms rotor current per phase,

R_r = rotor resistance, and

P_m' = mech. output power per phase.

AC Equivalent Circuit of Static Kramer Drive (cont'd)

Only the fundamental component of rotor current, I_{rf} needs to be considered. For a 6-step waveform,

$$I_{rf} = \frac{\sqrt{6}}{\pi} I_d$$

Thus, the rotor copper loss per phase is given by:

$$P_{rl}^{'} = I_r^2 R_r + \frac{1}{3} I_d^2 R_d = I_r^2 (R_r + 0.5 R_d)$$

AC Equivalent Circuit of Static Kramer Drive(cont'd)

The mechanical output power per phase is then given by:

P_m' = (fund. slip power) (1-s)/s

$$= \left[I_{rf}^2 (R_r + 0.5R_d) + \frac{\pi}{3\sqrt{6}} \frac{1.35V_L}{n_2} I_{rf} \left|\cos\alpha\right| \right] \frac{(1-s)}{s}$$