Chapter 1

INDUCTION MACHINES: AN INTRODUCTION

1.1. ELECTRIC ENERGY AND INDUCTION MOTORS

The level of prosperity of a community is related to its capability to produce goods and services. But producing goods and services is strongly related to the use of energy in an intelligent way.

Motion and temperature (heat) control are paramount in energy usage. Energy comes into use in a few forms such as thermal, mechanical and electrical.

Electrical energy, measured in kWh, represents more than 30% of all used energy and it is on the rise. Part of electrical energy is used directly to produce heat or light (in electrolysis, metallurgical arch furnaces, industrial space heating, lighting, etc.).

The larger part of electrical energy is converted into mechanical energy in electric motors. Among electric motors, induction motors are most used both for home appliances and in various industries [1-11].

This is so because they have been traditionally fed directly from the three-phase a.c. electric power grid through electromagnetic power switches with adequate protection. It is so convenient.

Small power induction motors, in most home appliances, are fed from the local single phase a.c. power grids. Induction motors are rugged and have moderate costs, explaining their popularity.

In developed countries today there are more than 3 kW of electric motors per person, today and most of it is from induction motors.

While most induction motors are still fed from three-phase or single-phase power grids, some are supplied through frequency changers (or power electronics converters) to provide variable speed.

In developed countries, 10% of all induction motor power is converted in variable speed drives applications. The annual growth rate of variable speed drives has been 9% in the last decade while the electric motor markets showed an average annual growth rate of 4% in the same time.

Variable speed drives with induction motors are used in transportation, pumps, compressors, ventilators, machine tools, robotics, hybrid or electric vehicles, washing machines, etc.

The forecast is that, in the next decade, up to 50% of all electric motors will be fed through power electronics with induction motors covering 60 to 70% of these new markets.

The ratings of induction motors vary from a few tens of watts to 33120 kW (45000 HP). The distribution of ratings in variable speed drives is shown in Table 1.1. [1]

Table 1.1. Variable speed a.c. drives ratings

Power (kW)	1 - 4	5 - 40	40 - 200	200 - 600	>600
Percentage	21%	26%	26%	16%	11%

Intelligent use of energy means higher productivity with lower active energy and lower losses at moderate costs. Reducing losses leads to lower environmental impact where the motor works and lower thermal and chemical impact at the electric power plant that produces the required electrical energy. Variable speed through variable frequency is paramount in achieving such goals. As a side effect, the use of variable speed drives leads to current harmonics pollution in the power grid and to electromagnetic interference (EMI) with the environment. So power quality and EMI have become new constraints on electric induction motor drives.

Digital control is now standard in variable speed drives while autonomous intelligent drives to be controlled and repaired via Internet are on the horizon. And new application opportunities abound: from digital appliances to hybrid and electric vehicles and more electric aircraft.

So much in the future, let us now go back to the first two invented induction motors.

1.2. A HISTORICAL TOUCH

Faraday discovered the electromagnetic induction law around 1831 and Maxwell formulated the laws of electricity (or Maxwell's equations) around 1860. The knowledge was ripe for the invention of the induction machine which has two fathers: Galileo Ferraris (1885) and Nicola Tesla (1886). Their induction machines are shown in Figure 1.1 and Figure 1.2.

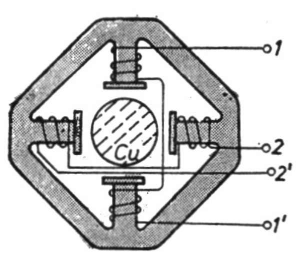


Figure 1.1 Ferrari's induction motor (1885)

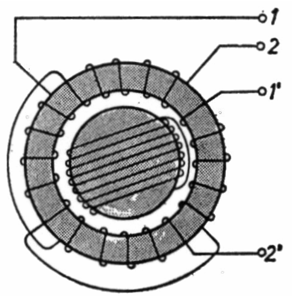


Figure 1.2 Tesla's induction motor (1886)

Both motors have been supplied from a two-phase a.c. power source and thus contained two phase concentrated coil windings 1-1' and 2-2' on the ferromagnetic stator core.

In Ferrari's patent the rotor was made of a copper cylinder, while in the Tesla's patent the rotor was made of a ferromagnetic cylinder provided with a short-circuited winding.

Though the contemporary induction motors have more elaborated topologies (Figure 1.3) and their performance is much better, the principle has remained basically the same.

That is, a multiphase a.c. stator winding produces a traveling field which induces voltages that produce currents in the short-circuited (or closed) windings of the rotor. The interaction between the stator produced field and the rotor induced currents produces torque and thus operates the induction motor. As the torque at zero rotor speed is nonzero, the induction motor is self-starting. The three-phase a.c. power grid capable of delivering energy at a distance to induction motors and other consumers has been put forward by Dolivo-Dobrovolsky around 1880.

In 1889, Dolivo-Dobrovolsky invented the induction motor with the wound rotor and subsequently the cage rotor in a topology very similar to that used today. He also invented the double-cage rotor.

Thus, around 1900 the induction motor was ready for wide industrial use. No wonder that before 1910, in Europe, locomotives provided with induction motor propulsion, were capable of delivering 200 km/h.

However, at least for transportation, the d.c. motor took over all markets until around 1985 when the IGBT PWM inverter was provided for efficient frequency changers. This promoted the induction motor spectacular comeback in variable speed drives with applications in all industries.

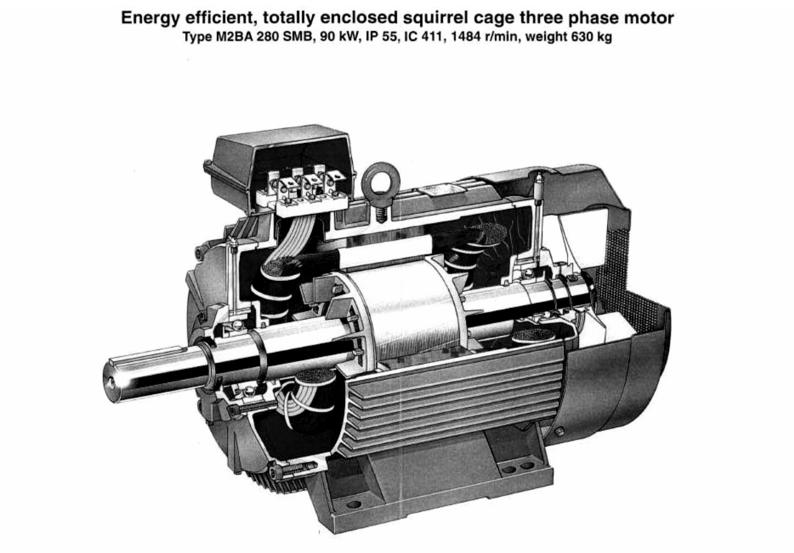


Figure 1.3 A state-of-the-art three-phase induction motor (source ABB motors)

Mainly due to power electronics and digital control, the induction motor may add to its old nickname of "the workhorse of industry" the label of "the racehorse of high-tech".

A more complete list of events that marked the induction motor history follows.

- Better and better analytical models for steady state and design purposes
- The orthogonal (circuit) and space phasor models for transients
- Better and better magnetic and insulation materials and cooling systems
- Design optimization deterministic and stochastic methods
- IGBT PWM frequency changers with low losses and high power density (kW/m^3) for moderate costs
- Finite element methods (FEMs) for field distribution analysis and coupled circuit-FEM models for comprehensive exploration of IMs with critical (high) magnetic and electric loading
- Developments of induction motors for super-high speeds and high powers
- A parallel history of linear induction motors with applications in linear motion control has unfolded
- New and better methods of manufacturing and testing for induction machines
- Integral induction motors: induction motors with the PWM converter integrated into one piece

1.3. INDUCTION MACHINES IN APPLICATIONS

Induction motors are, in general, supplied from single-phase or three-phase a.c. power grids.

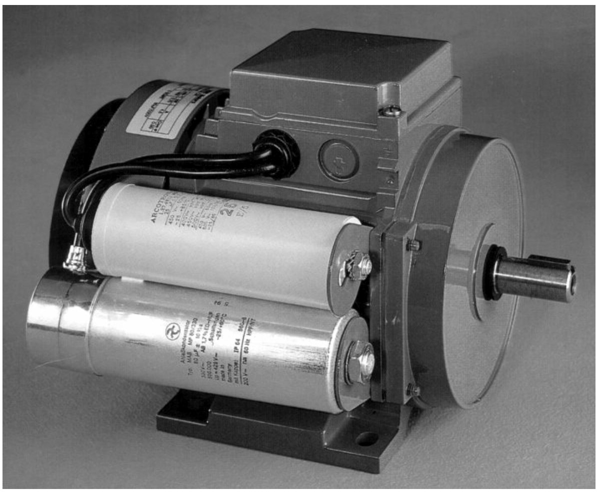


Figure 1.4 Start-run capacitor single phase induction motor (Source ABB)

Single-phase supply motors, which have two phase stator windings to provide selfstarting, are used mainly for home applications (fans, washing machines, etc.): 2.2 to 3 kW. A typical contemporary single-phase induction motor with dual (start and run) capacitor in the auxiliary phase is shown in Figure 1.4.

Three-phase induction motors are sometimes built with aluminum frames for general purpose applications below 55 kW (Figure 1.5).

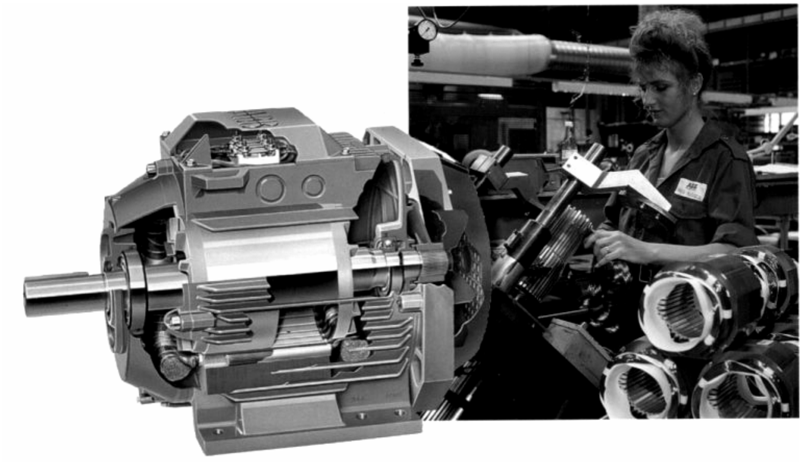


Figure 1.5 Aluminum frame induction motor (Source: ABB)

Table 1.2. EU efficiency classes

EU efficiency classes

Output kW	2-pole Boarderline EFF2/EFF3	EFF1/EFF2	4-pole Boarderline EFF2/EFF3	EFF1/EFF2
1.1	76.2	82.8	76.2	83.8
1.5	78.5	84.1	78.5	85.0
2.2	81.0	85.6	81.0	86.4
3	82.6	86.7	82.6	87.4
4	84.2	87.6	84.2	88.3
5.5	85.7	88.6	85.7	89.2
7.5	87.0	89.5	87.0	90.1
11	88.4	90.5	88.4	91.0
15	89.4	91.3	89.4	91.8
18.5	90.0	91.8	90.0	92.2
22	90.5	92.2	90.5	92.6
30	91.4	92.9	91.4	93.2
37	92.0	93.3	92.0	93.6
45	92.5	93.7	92.5	93.9
55	93.0	94.0	93.0	94.2
75	93.6	94.6	93.6	94.7
90	93.9	95.0	93.9	95.0

Besides standard motors (class B in the U.S.A. and EFF1 in EU), high efficiency classes (class E in U.S.A. and EFF2 and EFF3 in EU) have been developed. Table 1.2. shows data on EU efficiency classes EFF1, EFF2 and EFF3.

Even, 1 to 2% increase in efficiency produces notable energy savings, especially as the motor ratings go up.

Cast iron finned frame efficient motors up to 2000 kW are built today with axial exterior air cooling. The stator and rotor have laminated single stacks.

Typical values of efficiency and sound pressure for such motors built for voltages of 3800 to 11,500 V and 50 to 60 Hz are shown on Table 1.3 (source: ABB). For large starting torque, dual cage rotor induction motors are built (Figure 1.6).

Table 1.3.

Typical values of high voltage 4-pole machines.

Output kW	Efficiency % 4/4 load	3/4 load	1/2 load
500	96.7	96.7	96.1
630	97.0	97.0	96.4
710	97.1	97.1	96.5
800	97.3	97.2	96.8
900	97.4	97.4	96.9
1000	97.4	97.4	97.1
1250	97.6	97.7	97.5
1400	97.8	97.8	97.5
2000	97,9	97,8	97,5

Typical sound pressure levels in dB(A) at 1 meter distance

frame \ rpm	3000	1500	1000	≤750
315	79	78	76	-
355	79	78	76	-
400	79	78	76	75
450	80	78	76	75
500	80	78	76	75
560	80	78	76	75

The variation and measuring tolerance of the figures is ±3 dB(A).

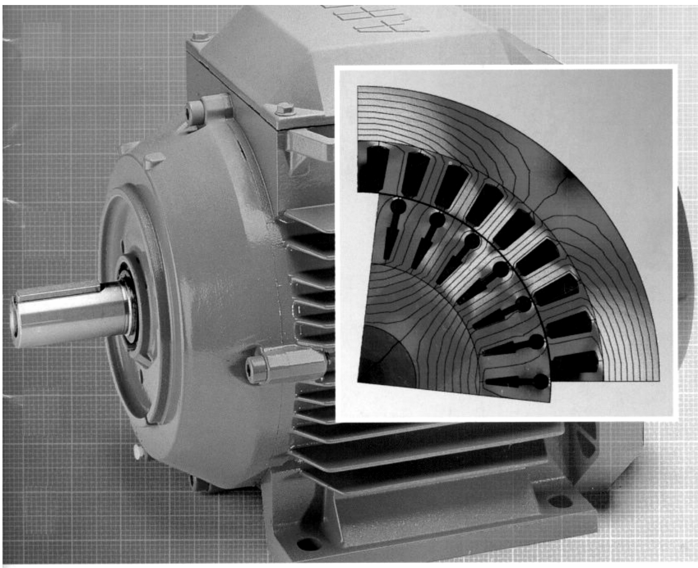


Figure 1.6 Dual cage rotor induction motors for large starting torque (source: ABB)

There are applications (such as overhead cranes) where for safety reasons, the induction motor should be braked quickly, when the motor is turned off. Such an induction motor with integrated brake is shown on Figure 1.7.

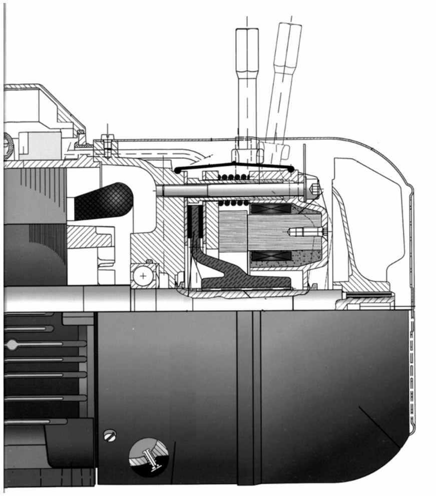


Figure 1.7 Induction motor with integrated electromagnetic brake (source: ABB)

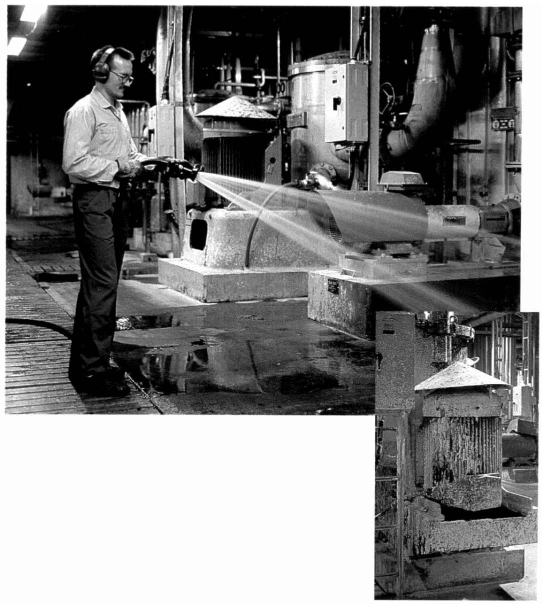


Figure 1.8 Induction motor in pulp and paper industries (source: ABB)

Induction motors used in the pulp and paper industry need to be kept clean from excess pulp fibres. Rated to IP55 protection class, such induction motors prevent the influence of ingress, dust, dirt, and damp (Figure 1.8).

Aluminum frames offer special corrosion protection. Bearing grease relief allows for greasing the motor while it is running.

Induction machines are extensively used for wind turbines up to 750 kW per unit and more. A typical dual winding (speed) induction generator with cage rotor is shown in Figure 1.9.

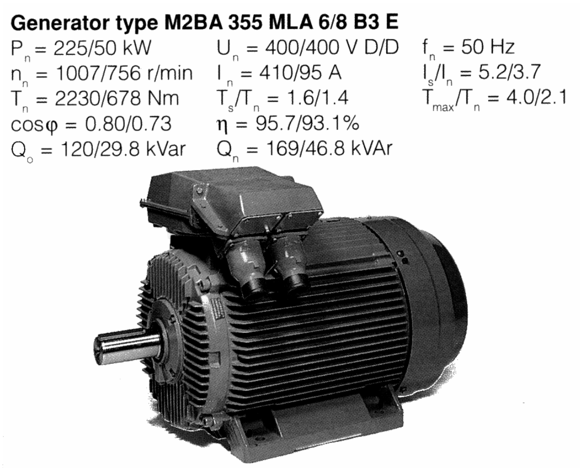


Figure 1.9 Dual stator winding induction generator for wind turbines (source: ABB)

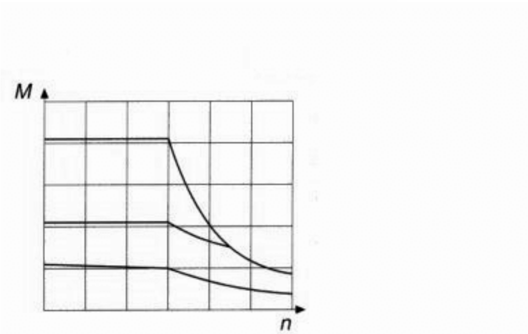
Wind power to electricity conversion has shown a steady growth since 1985. [2] The EU is planning to have 8000 MW of wind power plants by the year 2008. Today, about 3000 MW of wind power generators are at work worldwide, a good part in California.

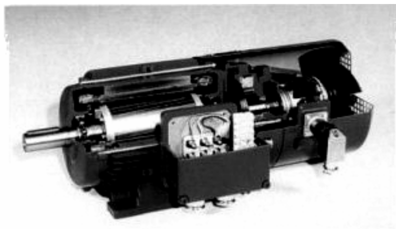
The environmentally clean solutions to energy conversion are likely to grow in the near future. A 10% coverage of electrical energy needs in many countries of the world seems within reach in the next 20 years. Also small power hydropower plants with induction generators may produce twice as that amount.

Induction motors are used more and more for variable speed applications in association with PWM converters.

Up to 2500 kW at 690 V (line voltage, RMS) PWM voltage source IGBT converters are used to produce variable speed drives with induction motors. A typical frequency converter with a special induction motor series are shown on Figure 1.10.

Constant cooling by integrated forced ventilation independent of motor speed provides high continuous torque capability at low speed in servodrive applications (machine tools, etc.).





SDM 602 motors

- 1.1 to 75 kW
- Maximum speed 6000 rpm
- Thermal reserves for high pull-out torque and good inverter efficiency
- Enhanced protection against voltage peaks
- Type of enclosure IP 54
- Constant cooling by integrated forced ventilation, independent of motor speed

Figure 1.10 Frequency converter with induction motor for variable speed applications (source: ABB)

Roller table motor,
frame size 355 SB, 35 kW

Roller table motor with a gear,
frame size 200 LB, 9.5 kW

Figure 1.11 Roller table induction motors without a.) and with b.) a gear (source: ABB)

Roller tables use several low speed, ($2p_1$ = 6-12 poles) induction motors with or without mechanical gears, supplied from one or more frequency converters for variable speeds.

The high torque load and high ambient temperature, humidity and dust may cause damage to induction motors unless they are properly designed and built.

Totally enclosed induction motors are fit for such demanding applications (Figure 1.11). Mining applications (hoists, trains, conveyors, etc.) are somewhat similar.

Induction motors are extensively used in marine environments for pumps, fans, compressors, etc. for power up to 700 kW or more. Due to the aggressive environment, they are totally enclosed and may have aluminum (at low power), steel, or cast iron frames (Figure 1.12).

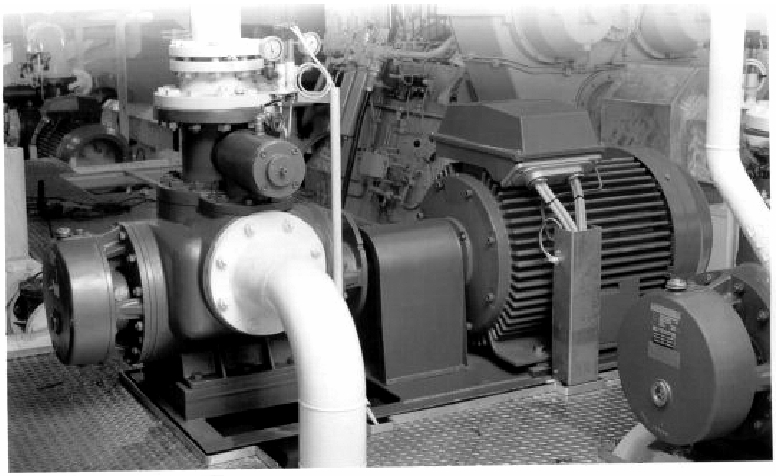


Figure 1.12 Induction motor driving a pump aboard a ship (source: ABB)

Aboard ship, energy consumption reduction is essential, especially money-wise, as electric energy is produced through a diesel engine electrical generator system.

Suppose that electric motors aboard a ship amount to 2000 kW running 8000 hours/year. With energy cost of U.S.$ 0.15/kWh, the energy bill difference per year between two induction motor supplies with 2% difference in motor efficiency is $0.02 \times 2000 \times 8000h \times 0.15$ = U.S.$ 55,200 per year.

Electric trains, light rail people movers in or around town, or trolleybuses of the last generation are propulsed by variable speed induction motor drives.

Most pumps, fans, conveyors, or compressors in various industries are driven by constant or variable speed induction motor drives.

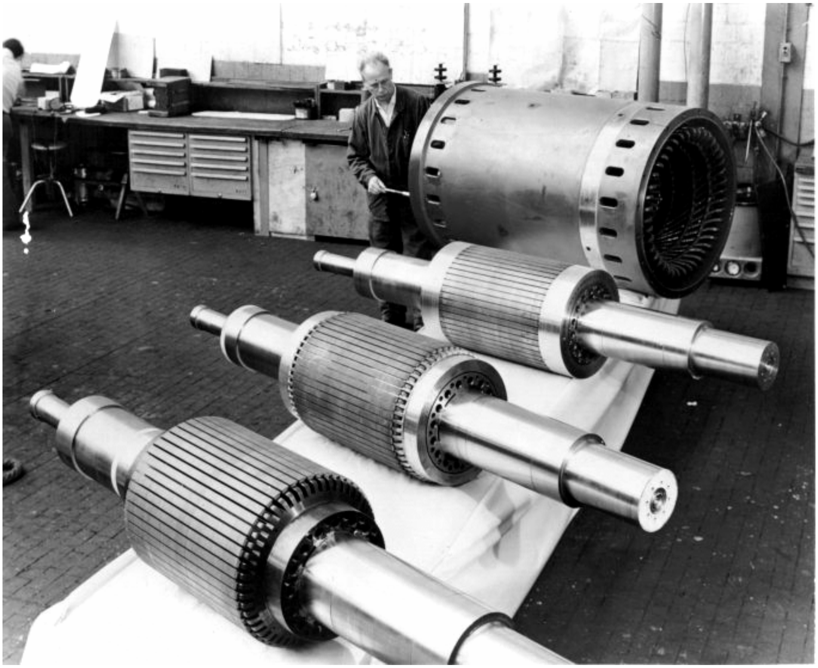


Figure 1.13 2500 kW, 3 kV, 24,000 rpm induction motor (source: ABB)

Figure 1.14 The BC transit system in Vancouver: with linear motion induction motor propulsion (source: UTDC)

The rotor of a 2500 kW, 3 kV, 400 Hz, 2 pole (24,000 rpm) induction motor in different stages of production as shown on Figure 1.13, proves the suitability of induction motors to high speed and high power applications.

Figure 1.15 shows a 3.68 kW (5 HP), 3200 Hz (62,000 rpm) induction motor, with direct water stator cooling, which weighs only 2.268 Kg (5 Pds). This is to show that it is the rather torque than the power that determines the electric motor size.

In parallel with the development of rotary induction motor, power electronics drives linear motion induction motors have witnessed intense studies with quite a few applications. [9, 10] Among them Figure 1.14 shows the UTDC-built linear induction motor people mover (BC transit) in Vancouver now in use for more than a decade.

The panoramic view of induction motor applications sketched above is only to demonstrate the extraordinary breadth of induction machine speed and power ratings and of its applications both for constant and variable speeds.

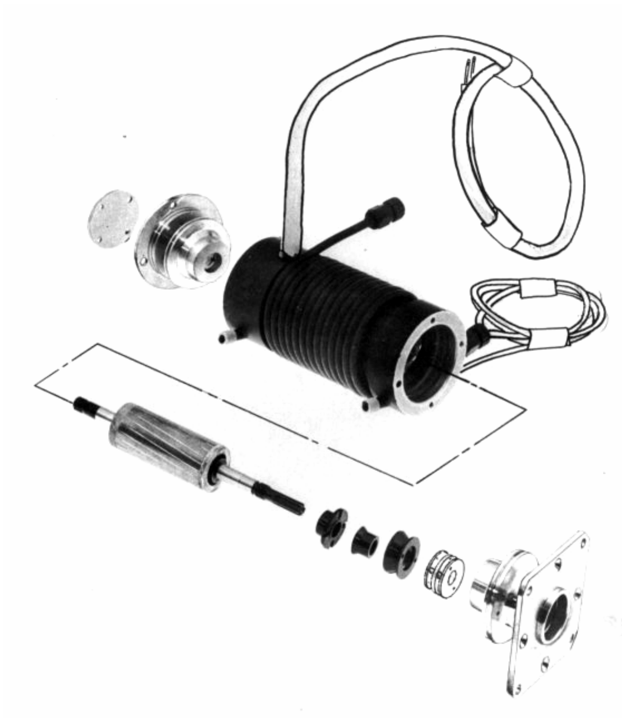


Figure 1.15 3.68 kW (5 HP), 3200 Hz (62,000 rpm) induction motor with forced liquid cooling

1.4. CONCLUSION

After 1885, more than one century from its invention, the induction motor steps into the 21st century with a vigour unparalleled by any other motor.

Power electronics, digital control, computer-added design, and new and better materials have earned the induction motor the new sobriquet of "the racehorse of industry" in addition to the earlier one of "the workhorse of industry".

Present in all industries and in home appliances in constant and variable speed applications, the induction motor seems now ready to make the electric starter/generator system aboard the hybrid vehicles of the near future.

The new challenges in modeling, and optimization design in the era of finite element methods, its control as a motor and generator for even better performance when supplied from PWM converters, and its enormous application potential hopefully justifies this rather comprehensive book on induction machines at the dawn of 21st century.

1.5. REFERENCES

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