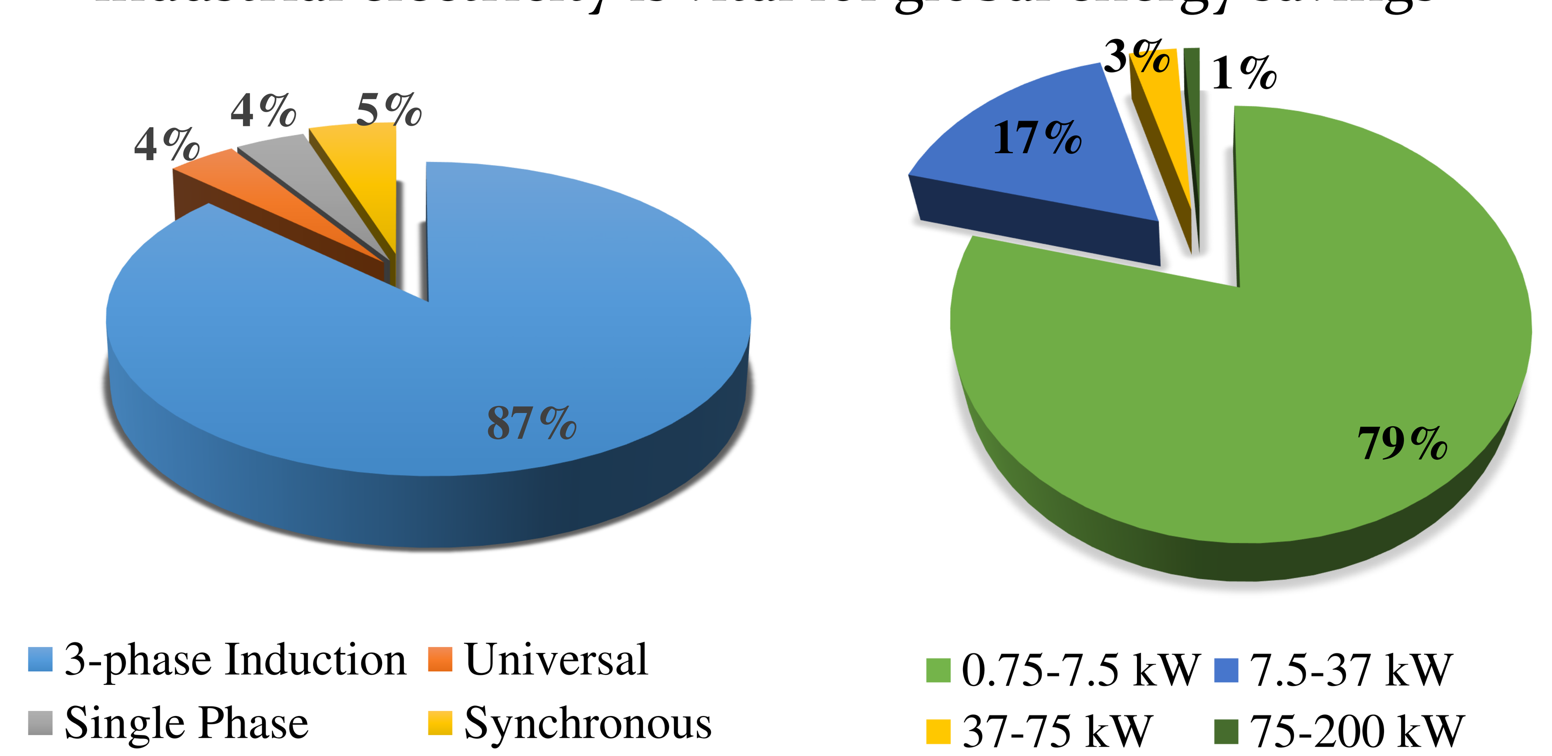
New Multilayer Winding Configuration for Distributed MMF in AC Machines with Shorter End-turn Length

Md Ashfanoor Kabir and Iqbal Husain

Background:

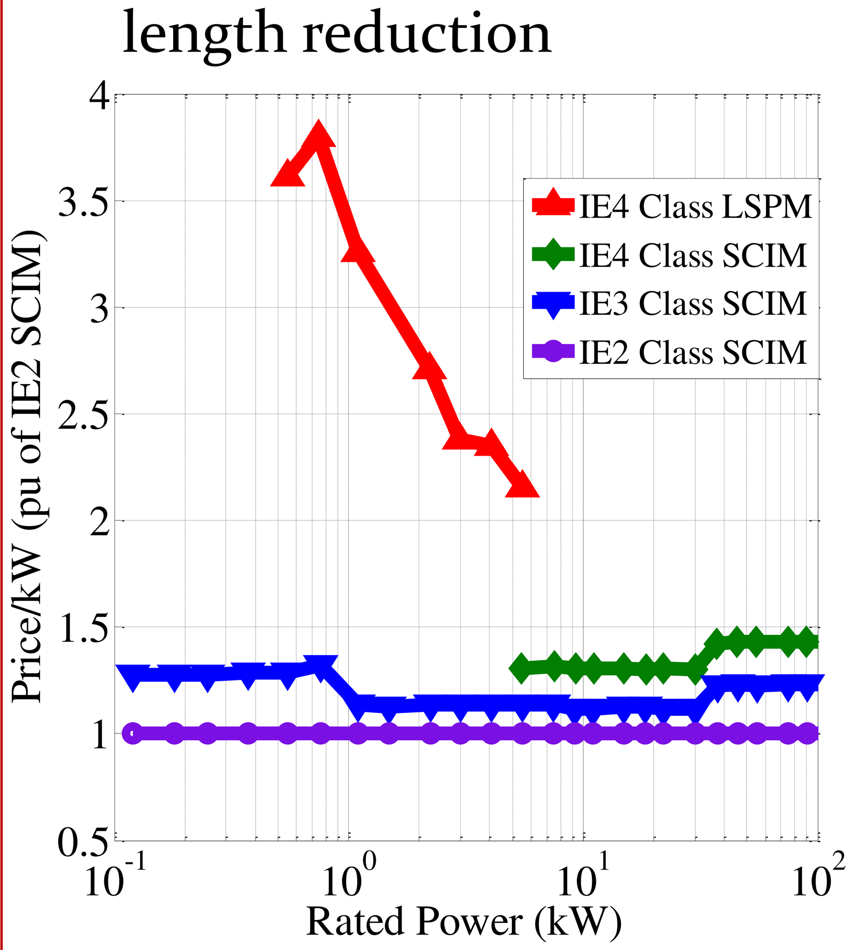
- Electric motors are the most prevalent electrical loads utilizing approximately 70% of industrial electricity
- Induction machines (IMs) hold the largest market share among different AC Motors
- Efficiency improvement for this major consumer of industrial electricity is vital for global energy savings



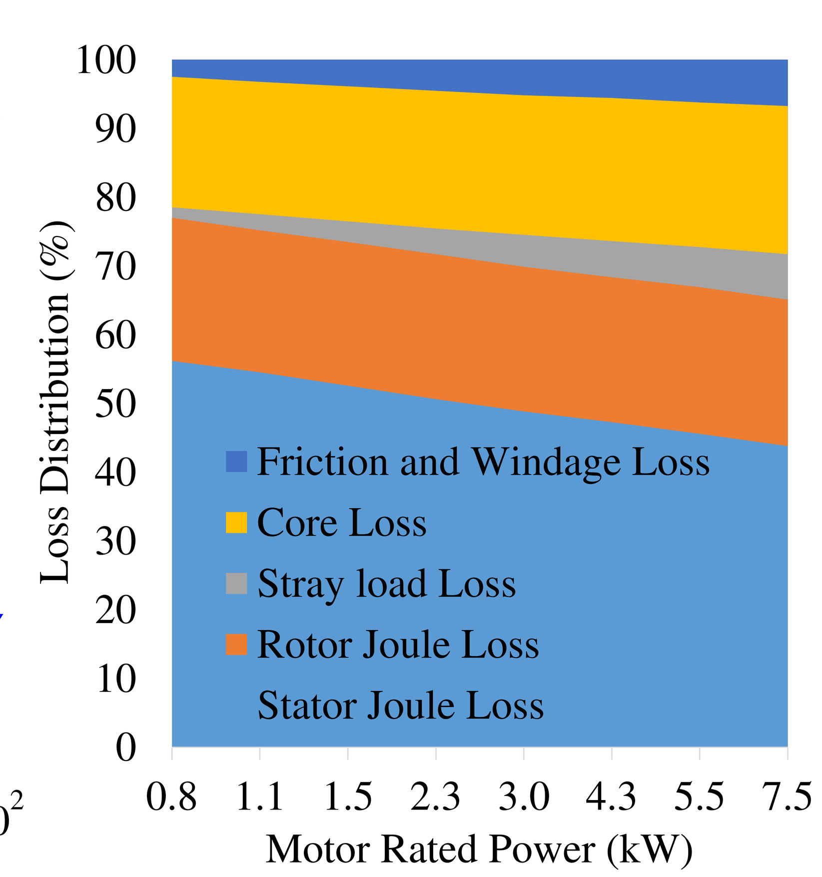
Market-share of integral AC motors in EU countries: share by machine type (left) and size (right) [2]

Motivation:

- Super premium efficiency squirrel cage induction machine (SCIM) available at power level ≥ 7.5 kW
- Lower power level: IE4 PMSM, price/kW is 2 to 4 times higher than SCIM
- Stator I²R loss share is highest (45-55%) in this power range
- Design Strategy: end-winding loss minimization through length reduction



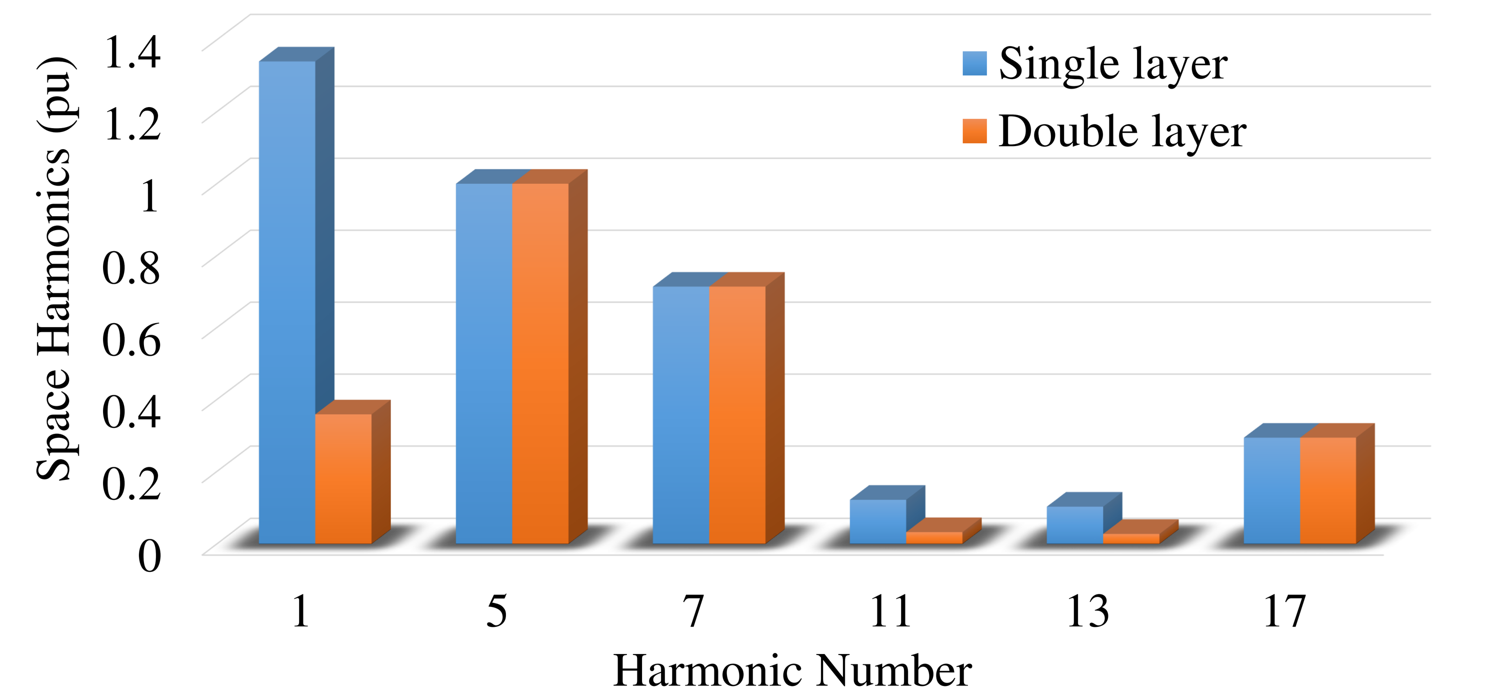
Price/kW for standard frame commercial machines [1]



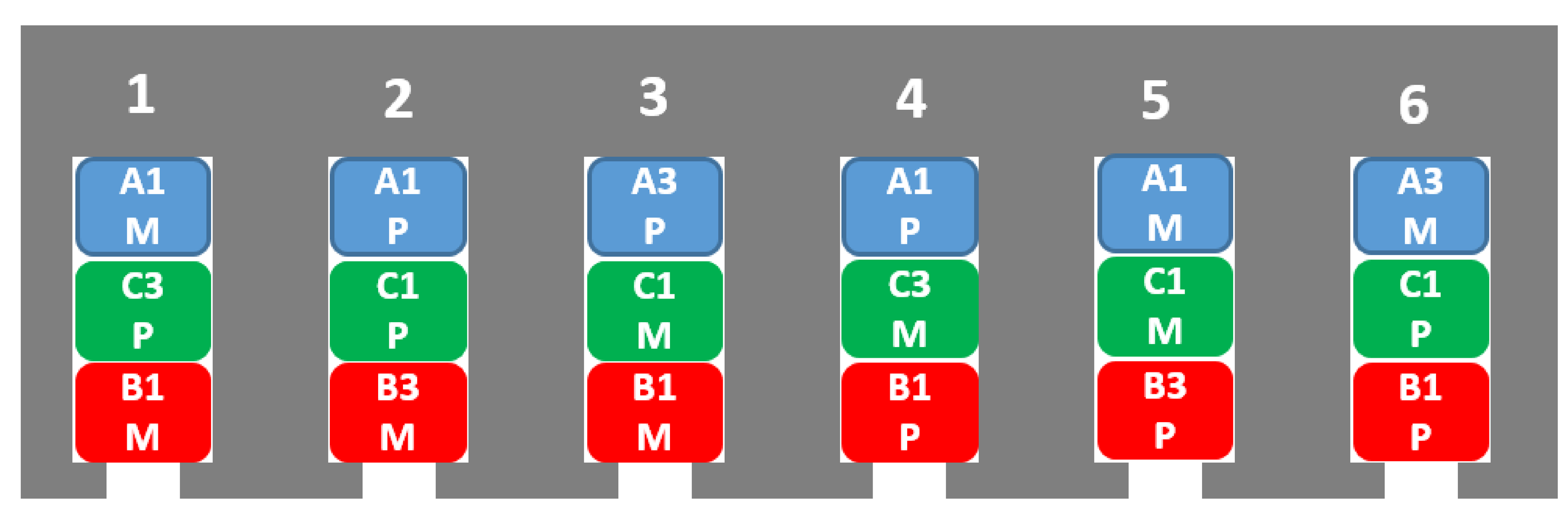
Induction Machine loss distribution (P_{rated} ≤7.5 kW)[4]

Design Challenges:

- Concentrated winding: short end-turn, high fill factor but high space harmonics in air-gap MMF
- Reduction in T_{AVG}, increase in P_{core} and rotor I^2R losses

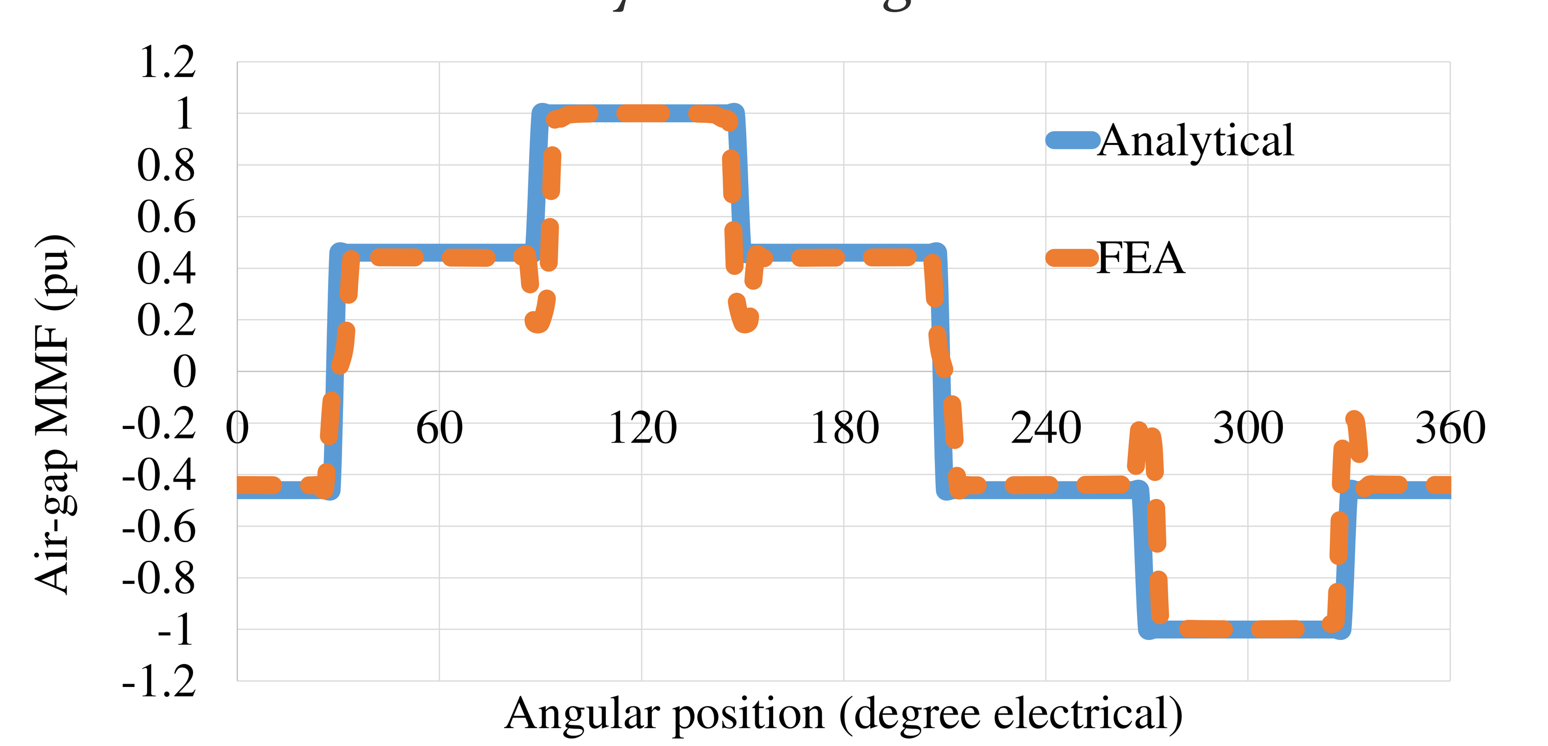


Proposed Multi-layer Winding:



Multi-layer winding in 12-Slot (ML12) distribution (half shown)

- New winding configuration includes both concentrated and overlapped windings in its structure
- Features: (a) shorter end-turn lengths with concentric fractional pitch and minimum full-pitch windings and (b) Sinusoidal MMF (low space harmonic contents)
- Total number of layers for a three phase machine will be three for this multilayer winding



Air-gap MMF verification for the design 12-slot multilayer winding

Performance Analysis:

Harmonic Number	Relative Amplitude (%)	
	MLCW [9]	ML12
1	15.52	100
5	100	27.71
7	74.40	7.62
11	0.84	14.66
13	0.79	0.42
17	25.67	9.85
19	26.05	2.01
THD	84.35	33.71

Harmonic Number	Relative Amplitude (%)	
	FPOL [10]	ML24
1	25.87	1
5	100	2.59
7	17.99	1.66
11	0.49	23.22
13	1.68	6.96
17	8.82	0.98
19	42.46	0.76
THD	53.63	24.47

Results:

Winding	DLDW	ML36
N_{turn}	80	
L_{cond} (mm)	194.2	179.65
L_{end} (mm)	114.2	99.65
R_{ph} (Ω)	7.63	7.06

Harmonic Number	Relative Amplitude (%)	
	DLDW	ML36
1	1	1
5	7.32	2.11
7	1.23	0.24
11	0.88	1.05
13	2.95	6.54
17	22.57	23.82
19	12.33	11.57

- ML end-winding 12.74% shorter compared to DLDW
- Reduction of R_{PH} by 7.5%
- ML provides sinusoidal air-gap MMF similar to DLDW
- Rated performance compared with a benchmark IE3 SCIM
- Evaluation under the same stator I^2R loss shows higher torque density with ML36
- Cooler and higher efficiency yieldable with multi-layer SCIM

Parameters	Results	
Winding Type	DLDW	ML36
Phase V_{RMS} (V)	287.8	298.43
Fund. $F_{Electrical}$ (Hz)	60	
Stator I²R Loss (% of P_{OUT})	8.18	7.80
Rotor I²R Loss (% of P_{OUT})	1.65	1.57
Core loss (% of P_{OUT})	2.49	2.5
Input Power, P_{IN} (W)	913.34	942.03
Average Torque, T_{AVG} (Nm)	4.32	4.50
Rated Speed (rpm)	1745	
Output Power, P_{OUT} (W)	789.42	822.31
η (%)	86.43	87.3
Power factor	0.745	0.741