Variable Characteristics Motors (Matrix motor and CMMF motor)

Kan Akatsu
Shibaura Institute of Technology, Dept. of Electrical Engineering
akatsu@sic.shibaura-it.ac.jp

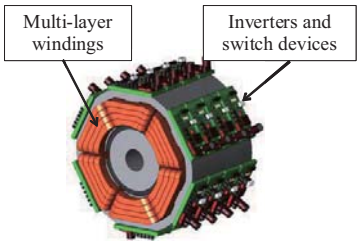
Abstract :
Variable Characteristic motors which can change the magnet flux have been focused since these motors can improve the low load efficiency and also can reduce the magnet quantity. This paper introduces 2 new motors, the one has a changeable winding connection; named as Matrix Motor and another one has compounded magnet-motive forces; named as CMMF motor. These motors are realized by integration of motor and power electronics.

Variable Characteristics Motors (Matrix Motors and CMMF Motors)

Kan Akatsu
Shibaura Institute of Technology
Department of Electrical Engineering

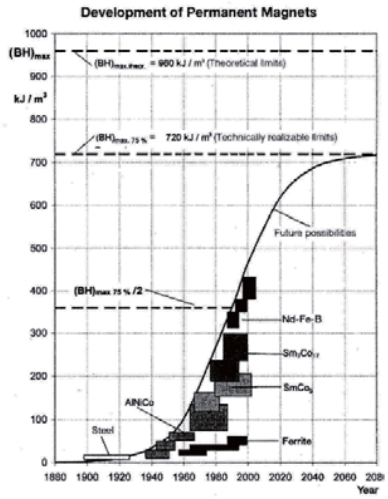
Presentation Outline

1. Research background
2. Approaching from the stator (MATRIX motor)
3. Approaching from the rotor (CMMF motor)
4. Conclusion



Technology That is Hard to Catch Up On?

- There is no more room for static characteristic improvement
  - Torque density→Magnet BH_{max} limit
  - Output density→Higher speed and voltage
    - 1:10 is the limit, insulation problem
  - Efficiency→Large material dependence



- We must look toward dynamic characteristics
  - Torque quality→Ride quality improvement, noise reduction
  - Operating range expansion→High quality torque in the high speed areas
  - Higher efficiency in the operating range→Expanding the high efficiency range

High-value Added Motor Research

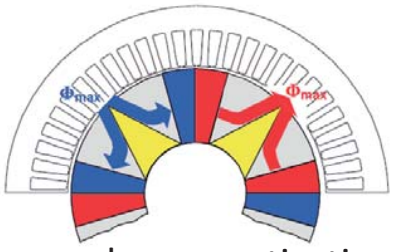
- Merging power electronics and controls
  - Unique drive type and control type
  - A motor that cannot be imitated even if it is taken apart
  - A normal motor with modifications (variable characteristics)

- MATRIX motors (variable stator characteristics)
- Compounded magnet-motive force motor (variable rotor characteristics)

Constant variable motor research

Variable rotor

"Variable magnetic force motor"



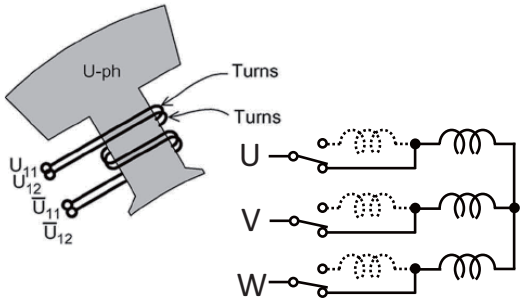
re- or de-magnetization

Reference: V. Ostovic

- ○ High level of freedom
- × Inverter capacity

Variable stator

"Armature coil switch"



Reference: Yaskawa Electric

- ○ Simple circuit composition
- × Low level of freedom

MATRIX Motor

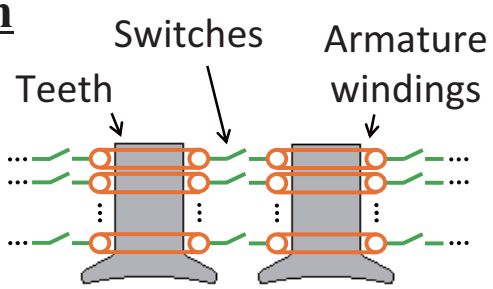
Objective: Higher efficiency in operating range through characteristic variables

Stator variables

2. MATRIX Motor

☐ The proposal of this research

Several coils + Several switches



Achieving "constant variables"

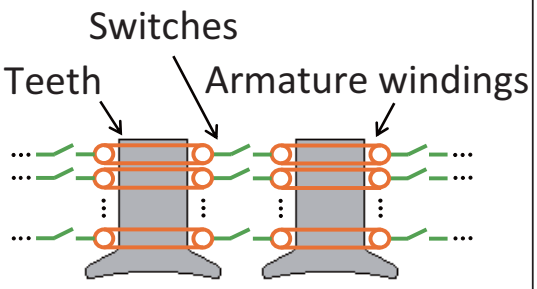
- ✓ **Number of coils** ➢ Induced voltage amplitude
- ✓ **Coil factors** ➢ Induced voltage harmonic components
- ✓ **Series/parallel connections** ➢ Coil resistance

☐ Matrix motor flow

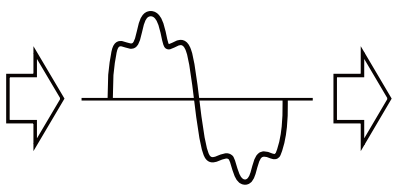
The command for an arbitrary excitation waveform

$$\begin{bmatrix} 0 & 1 & \cdots & 0 \\ 1 & 0 & & \vdots \\ \vdots & & \ddots & 1 \\ 0 & \cdots & 1 & 0 \end{bmatrix}$$

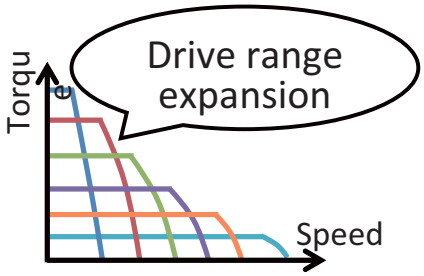
Matrix command



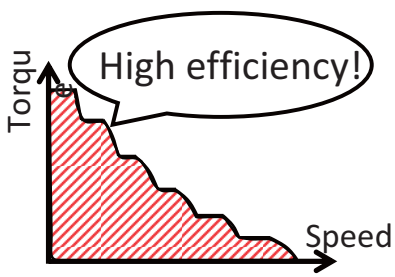
Coil switchover



Arbitrary excitation waveform



N-T characteristics

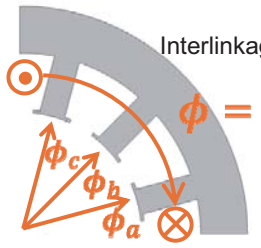


Efficiency distribution

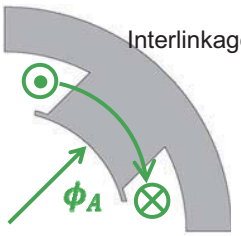
The Principle Behind Matrix Motors

☐ Interlinkage magnetic flux vectors

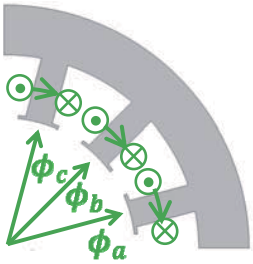
➢ Distributed winding



➢ Concentrated winding



➢ **The proposal of this research**



Series connection of adjacent concentrated windings

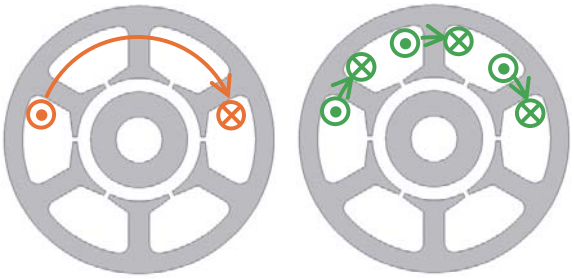
$\phi = \phi_a + \phi_b + \phi_c$

Achieving distributed winding flux interlinkage numbers

☐ Armature flux interlinkage numbers

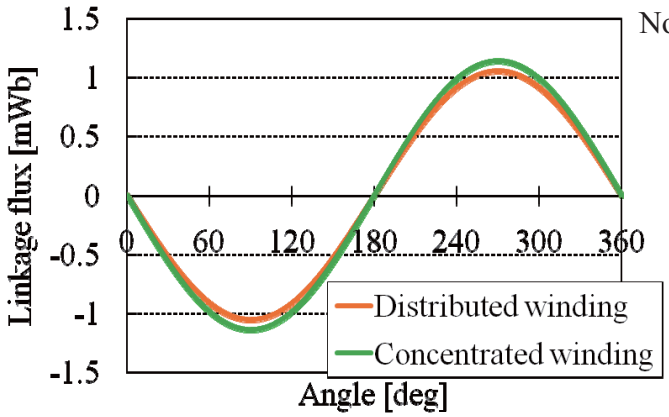
✓ No magnet

✓ Input current i = 2 [Apeak]



Normal distributed winding

Distributed winding via concentrated winding



Concentrated winding interlinkage flux Many

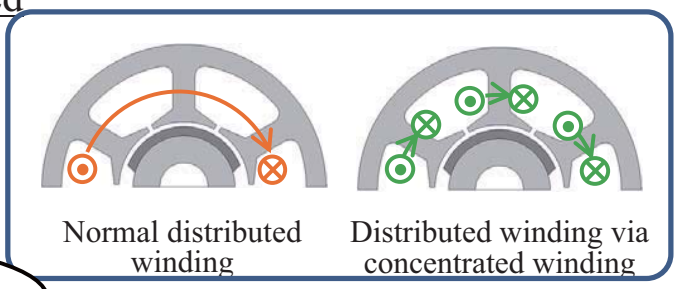
Depends on the distance between coils

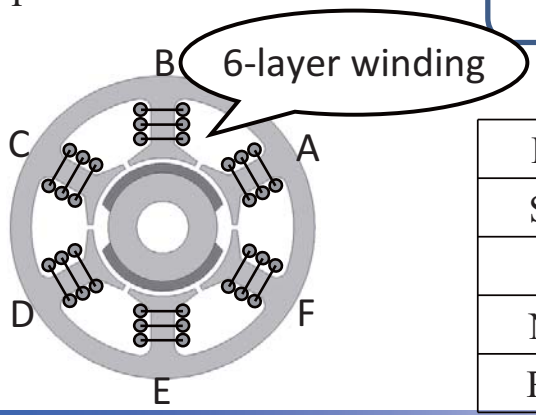
Armature flux interlinkage number (JMAG analysis result)

Basic Characteristics of a Matrix Motor

☐ Basic verification model

- ✓ Switch between concentrated and distributed winding
- ✓ All pitch winding
- ✓ Number of poles pairs: 1





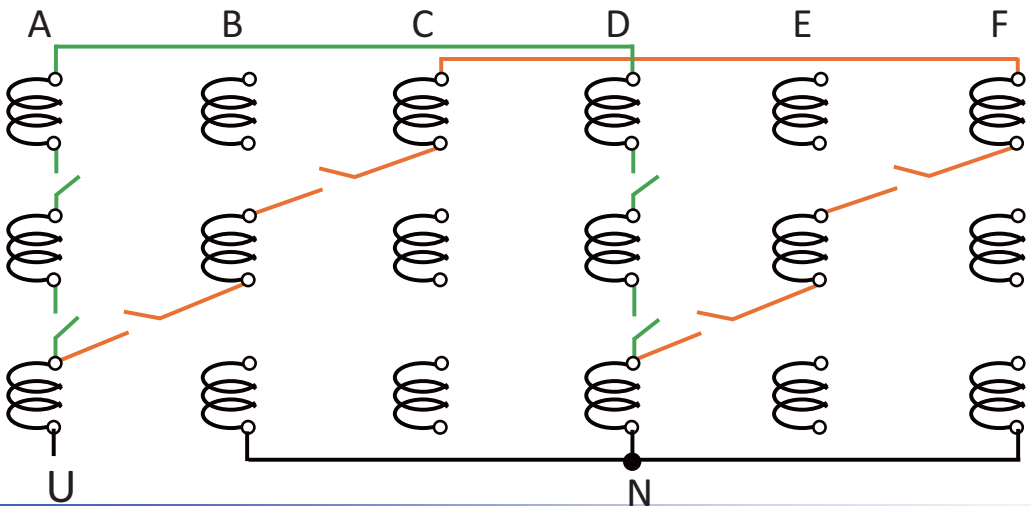
Motor condition

Rotor diameter [mm]	24.5
Stator diameter [mm]	58.0
Stack length [mm]	20.15
Number of turn[/slot]	20×3
Resistance [mΩ/coil]	52.2

Basic Characteristics of a Matrix Motor

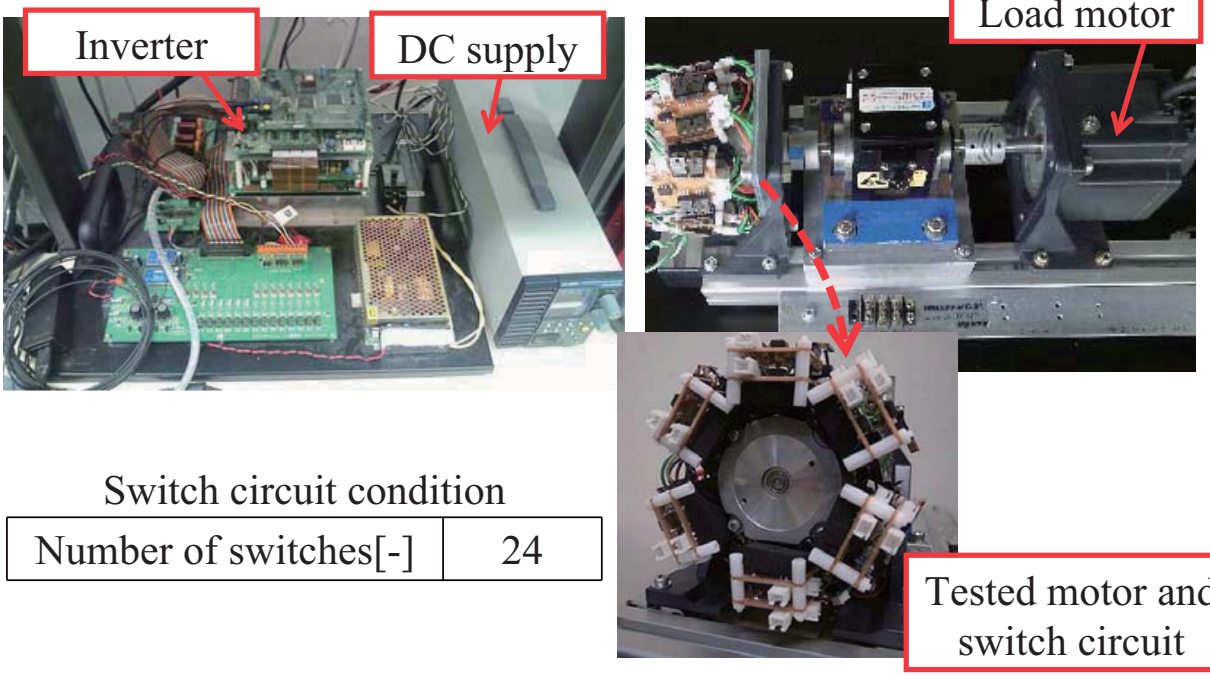
Connects with the same slot ⇨ ☐ (CWD) Concentrated Winding Drive

Connects with the adjacent slot ⇨ ☐ (DWD) Distributed Winding Drive



Basic Characteristics of a Matrix Motor

☐ Experimental equipment



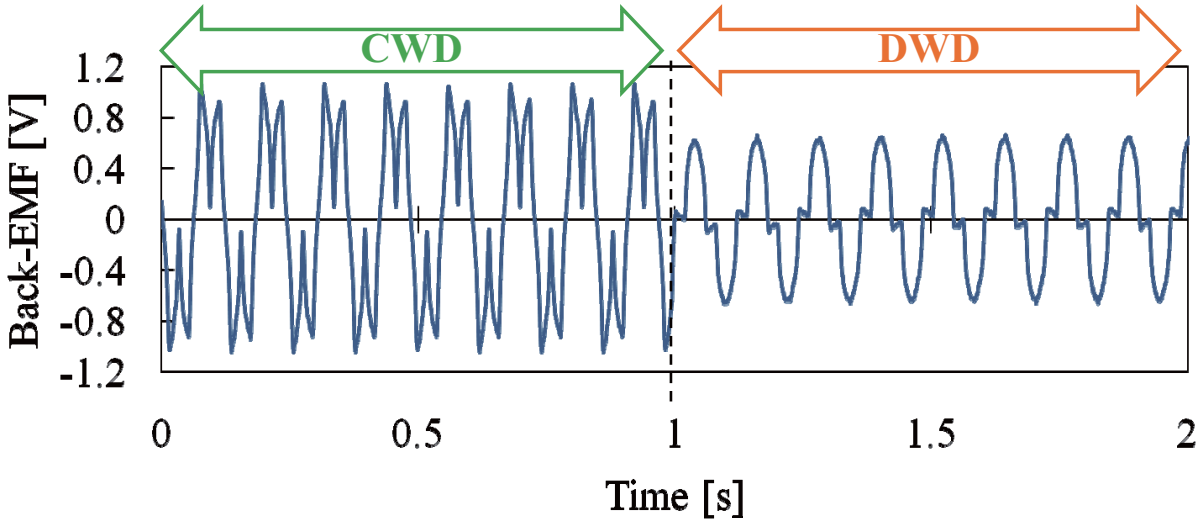
Switch circuit condition

Number of switches[-]	24

Basic Characteristics of a Matrix Motor

☐ No-load induced voltage characteristics

Switching between CWD and DWD during fixed rotation of 500rpm in a load motor



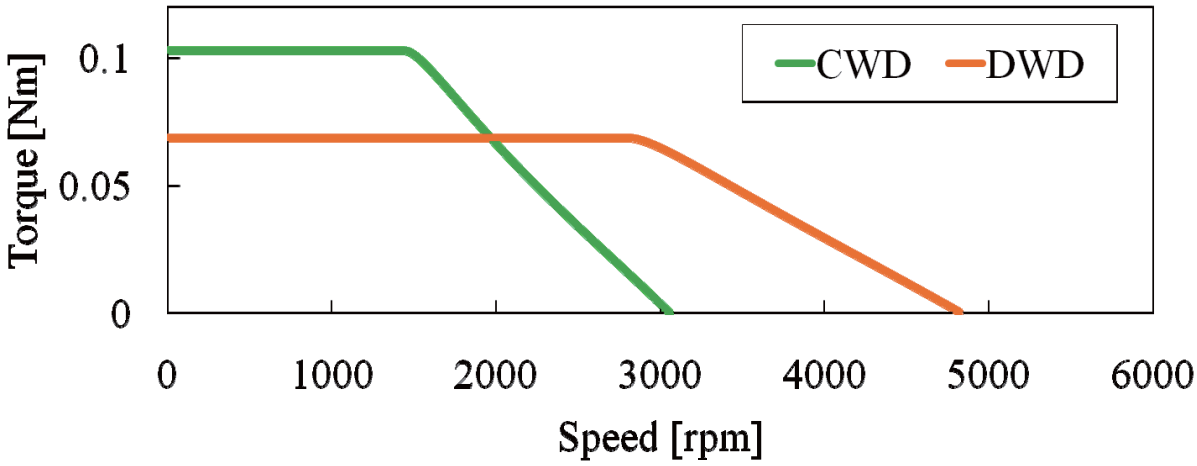
Variations in induced voltage amplitude and harmonics

Basic Characteristics of a Matrix Motor

☐ *Speed–torque (N–T) characteristics*

Comparing N-T characteristics between CWD and DWD

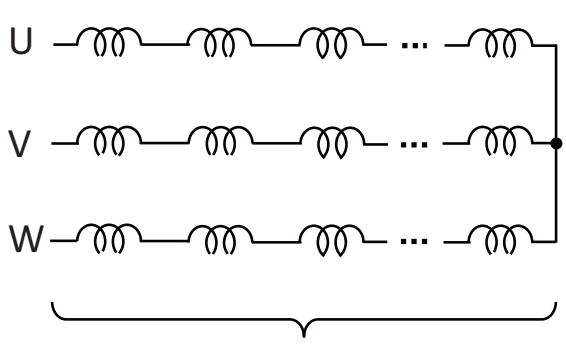
DC bus voltage V_{DC} = 15V Max. current I_{rms} = 3A Switch resistance R_{sw} = 0 Ω



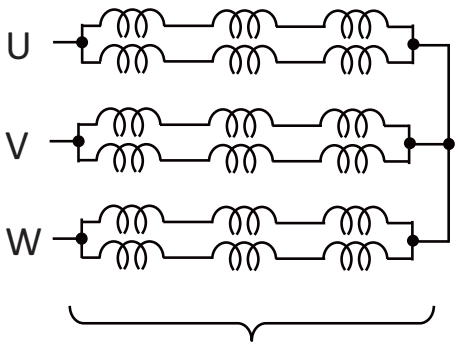
Variations in drive range via an increase in flux interlinkage numbers

Basic Characteristics of a Matrix Motor

☐ Series–parallel connection



6 series connections



3 series – 2 parallel connections

CWD
DWD
×
Series connection (6 series)
Parallel connection (3 series-2parallel)

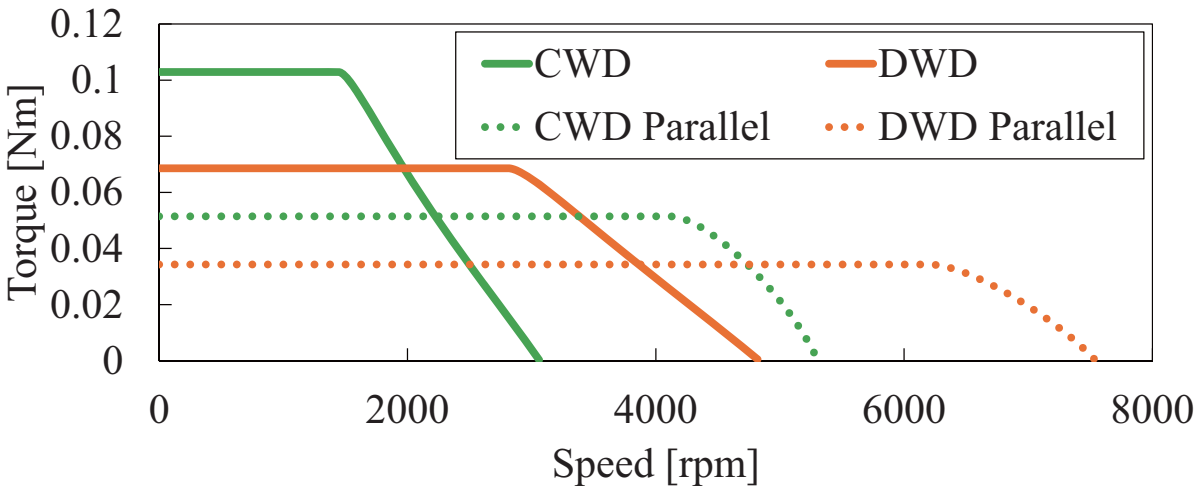
☐ *Motor parameters (analysis values from JMAG)*

Parameter	CWD	DWD	CWD Parallel	DWD Parallel
Magnet flux [mWb]	19.8	13.2	9.90	6.60
d-axis inductance [mH]	1.16	0.516	0.280	0.127
q-axis inductance [mH]	1.25	0.566	0.310	0.141
Resistance [mΩ/phase]	313.2	313.2	78.3	78.3
Number of turn [/phase]	120	40	120	40
Winding factor [-]	0.5	1	0.5	1

Basic Characteristics of a Matrix Motor

☐ *Speed–torque (N–T) characteristics*

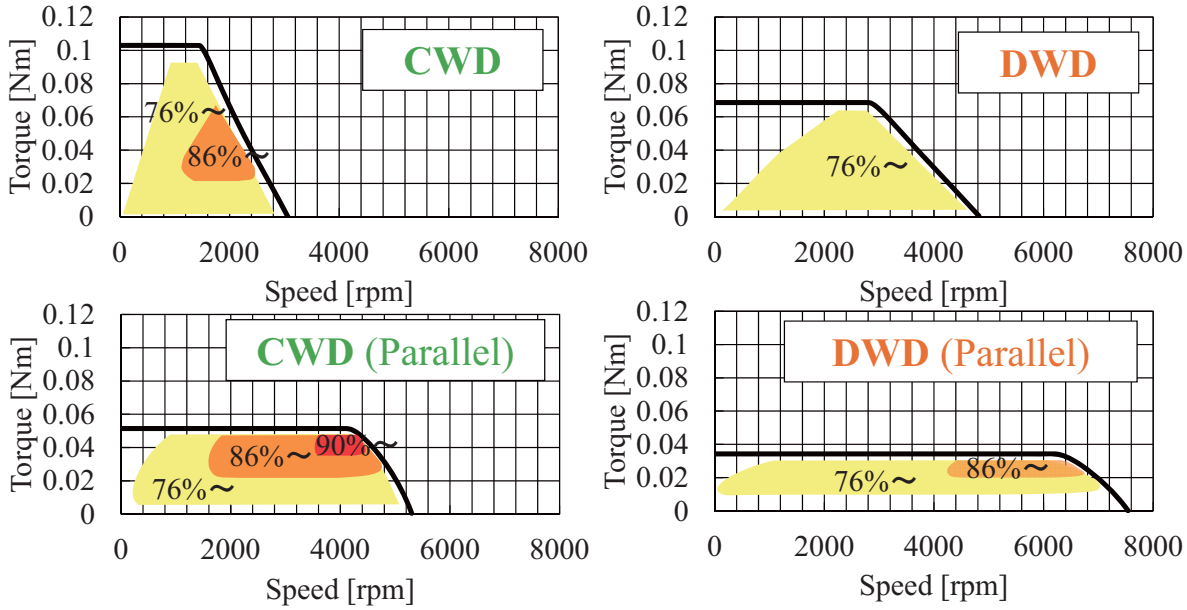
DC bus voltage V_{DC} = 15V Max. current I_{rms} = 3A Switch resistance R_{sw} = 0 Ω



Variations in drive range via an increase in flux interlinkage numbers

Basic Characteristics of a Matrix Motor

Efficiency characteristic



Variations in high efficiency range via an increase in coil resistance and flux interlinkage numbers

Matrix Motor Summary

- We confirmed that, due to a combination of both the coil's series and parallel as well as its concentrated and distributed coil topologies, variations in a motor's interlinkage flux numbers and impedance become possible, so we are able to achieve high efficiency in a broad range.
- It becomes possible to handle various situations including independent current controls for each phase, and not just switching coils
- And last but not least, it is 1 turn, 1 switch!

3. CMMF Motor (Compound Magnet Motive Force)

Objective: Higher efficiency in the operating range through characteristic variations.

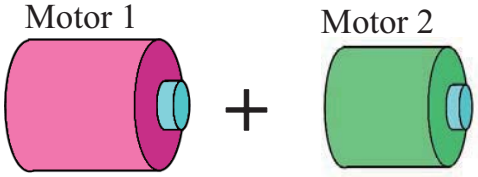
Research Background

The proposed motor:

outputs several characteristics with a special magnet location.

A motor that uses compound magnet-motive force

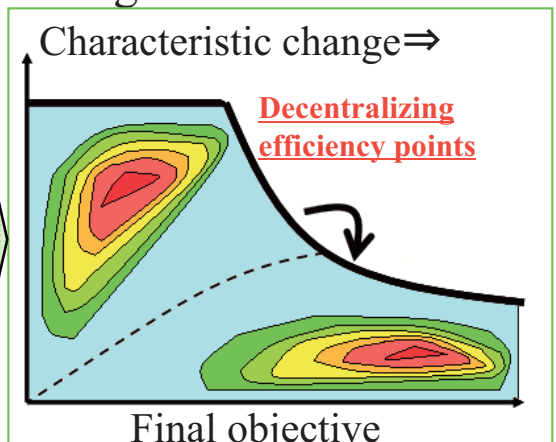
Multi-motor parameters



It is as though there are several motors…

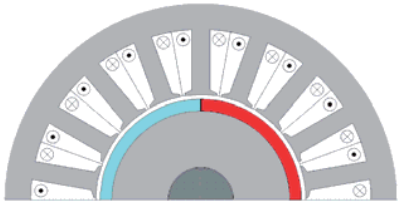
- It has the characteristics of several motors
- It has several parameters

Change its characteristics



Compound Magnet Motive Force (CMMF) Motor

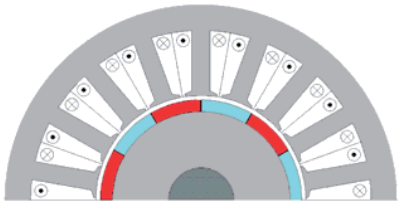
How did we get it to have several characteristics??



4 magnetic poles
12 magnetic poles

4 pole magnet motor (9 phase drive)

Compound



12 pole magnet motor (3 phase drive)

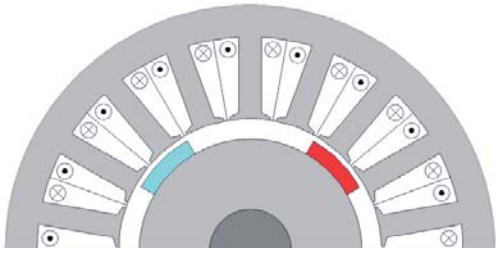


Fig. 3 CMMF motor ½ model

・**2 types** of motor parameters

・**3 types of characteristics** are possible to use

See more about the magnet location＝＞

Magnet Location and CMMF

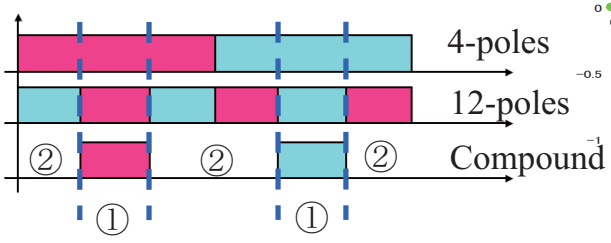
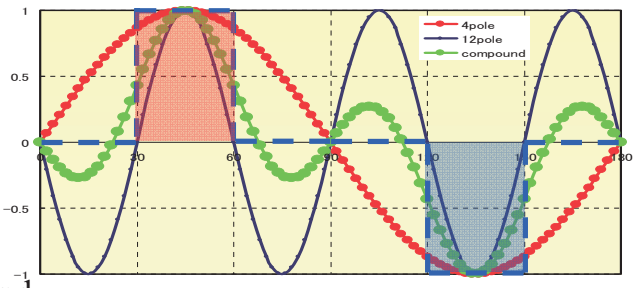


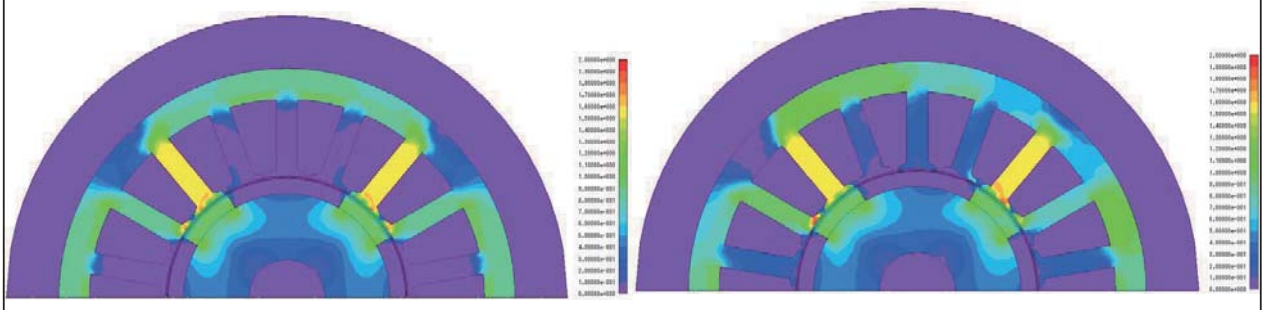
Fig. 4 Motor model and magnet location



・Red＝**1st harmonic** fundamental wave
・Blue＝**3rd harmonic** fundamental wave

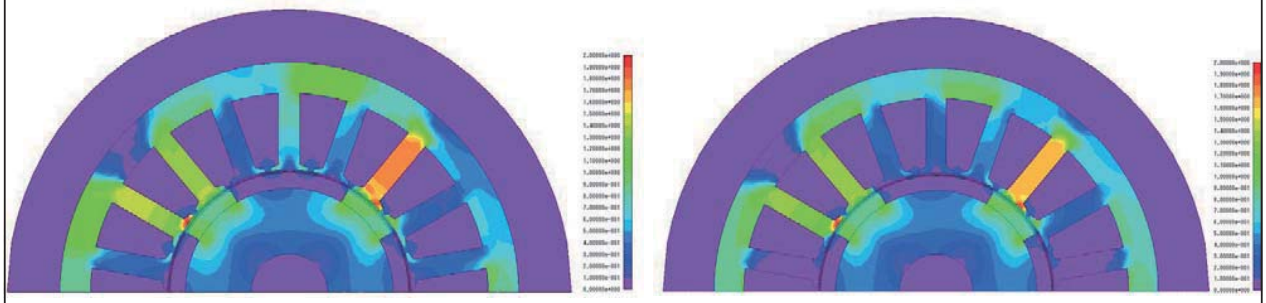
・It superimposes the rotors with different pole numbers and only leaves behind (**N-N**, **S-S**) ①
⇒It can leave behind 2 types of characteristics. (**N-S**) disappears ②
・The harmonics that came from compounding displace the 12 poles by π and minimize them

Compound Magnet Motive Force (CMMF) Motor



During no-load

During 4 pole drive (9 phase drive)



During 12 pole drive (3 phase drive)

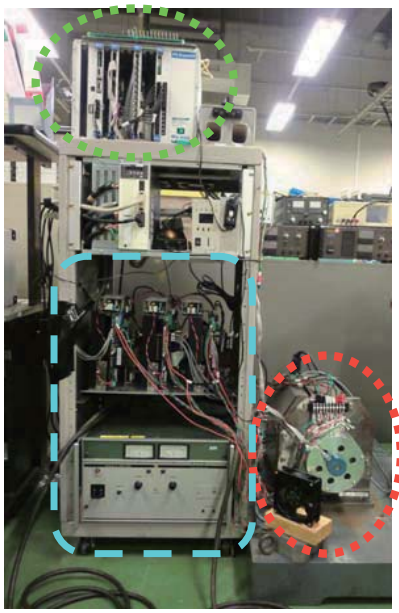
During compound drive
(Compound drive)

a) The experimental system and experimental equipment

Controller

9.1 kVA Inverter × 3, DC power source 2 kVA

Trial motor (CMMF motor)



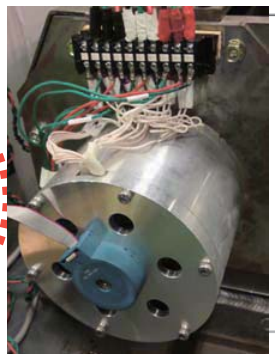
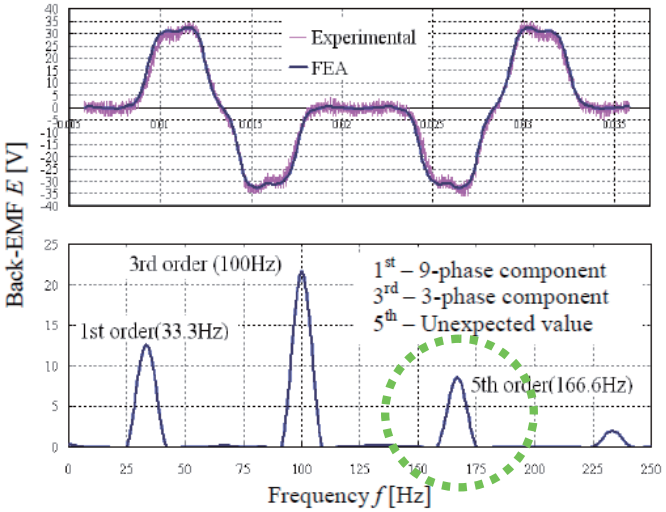


Table 1 Motor specs

Diameter of Rotor	68	[mm]
Diameter of Stator	130	[mm]
Magnet length	4.5	[mm]
Magnet reduction rate	η_3=0.333,	η_9=0.5
Winding factor	k_3=0.866,	k_9=0.342
Gap length	1.5	[mm]
Stack length L	50	[mm]
The number of turns N	93	[turns]
The number of slots SL	18	

b) No-load trial - results



・FEA and actual trial results match

・**2 characteristic components** confirmed

(4 poles=9 ϕ , 12 poles=3 ϕ)

・Confirmation of the 5th harmonic component from FFT

=>Invalid component

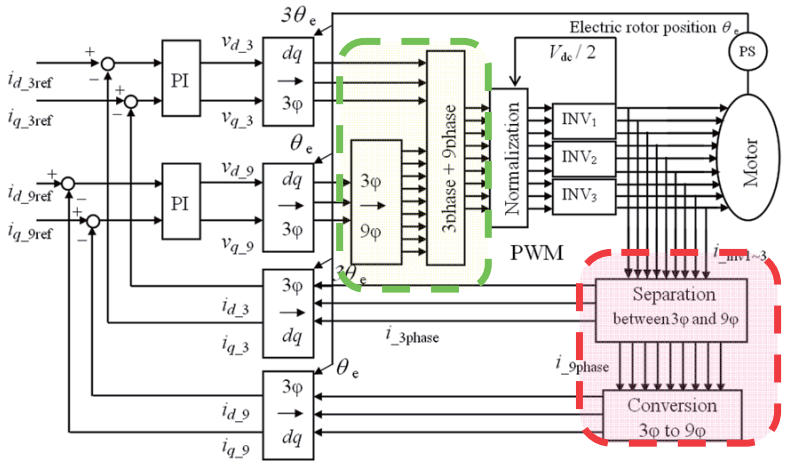
Fig. 5 Terminal inducted voltage waveform and FFT results

=>2 types of magnetic flux (**Compound characteristic**)＋5th harmonic confirmed

c) Current—torque characteristics- current method

3 phase

9 phase



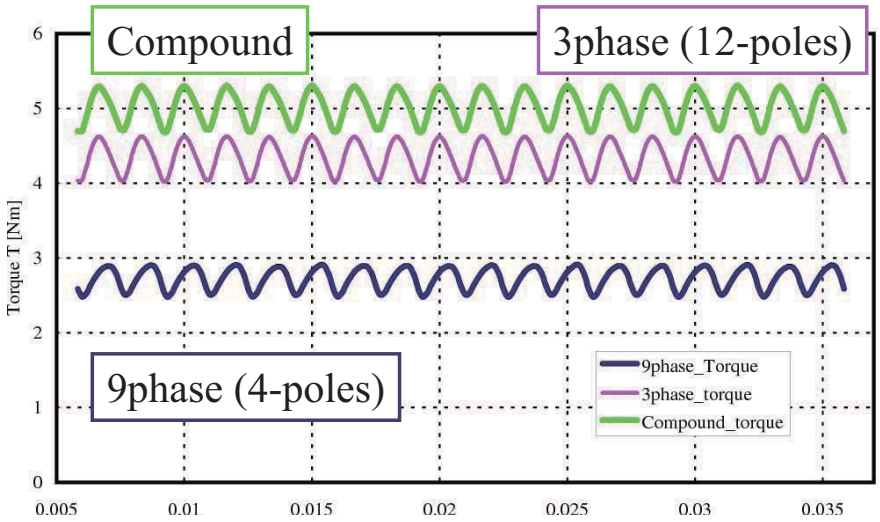
3-9 phase separation & 3-9 phase transformation

Fig. 6 Controls are blocked because of compound current

・9 phase, 3 phase, and compound drives are possible due to the controls based on Fig. 6.

・Combine the reference values from the 3 phase and 9 phase to make them the reference value.

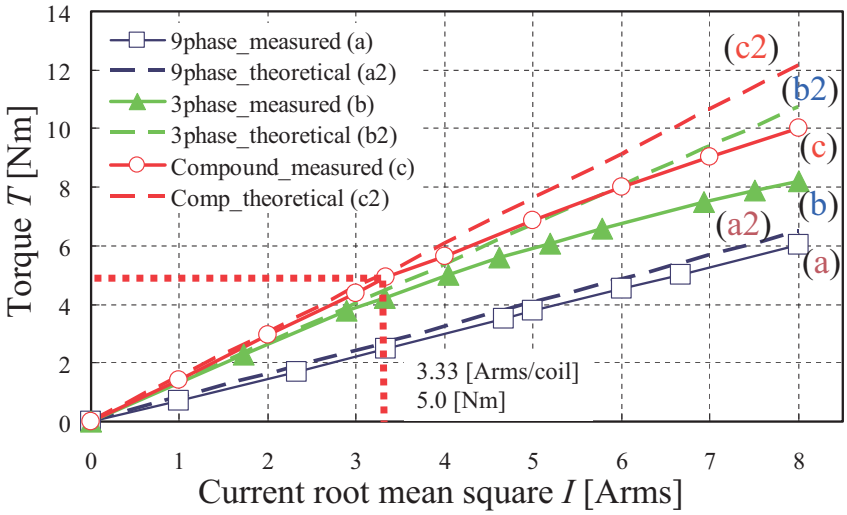
c) Current—torque characteristics - FEA torque waveform



An FEA output torque waveform comparison for when the current is distributed in the effective value

=>The compound drive is able to put out the most torque.
=>The coil factor is low for the 4 poles (0.342)

c) Current—torque characteristics



The comparison model

Same volume, **magnet quantity doubles**
5[Nm], 3.33Arms

- Linearity of the current-torque characteristics- Confirming the saturation characteristics

⇒3 phase is saturated, 9 phase resists saturation strongly

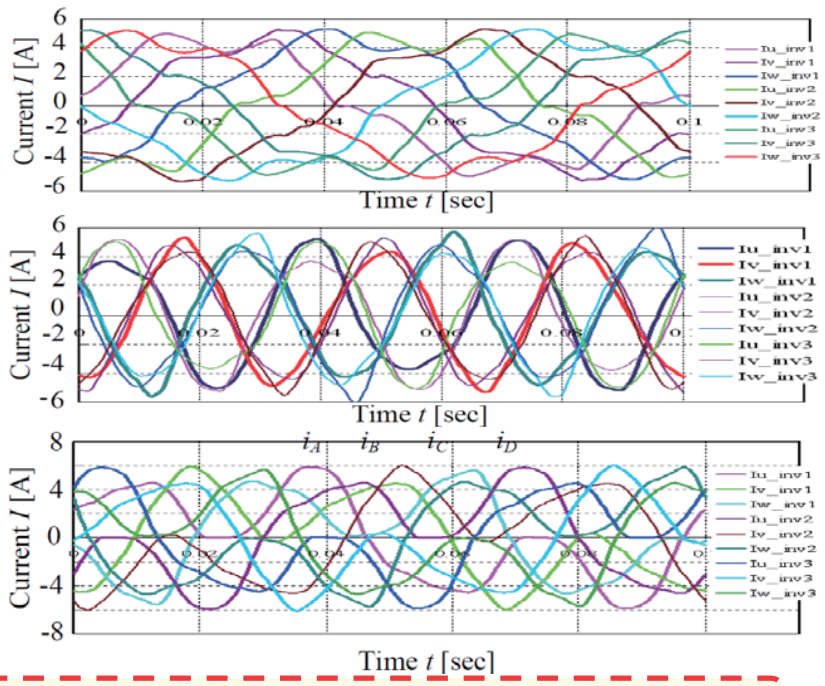
- **Magnet quantity is half,** 3.33[Arms] and **the output torque is equivalent to the comparison motor**

c) Current—torque characteristics – Current waveform for *irms*=3.33[A]

9 phase current

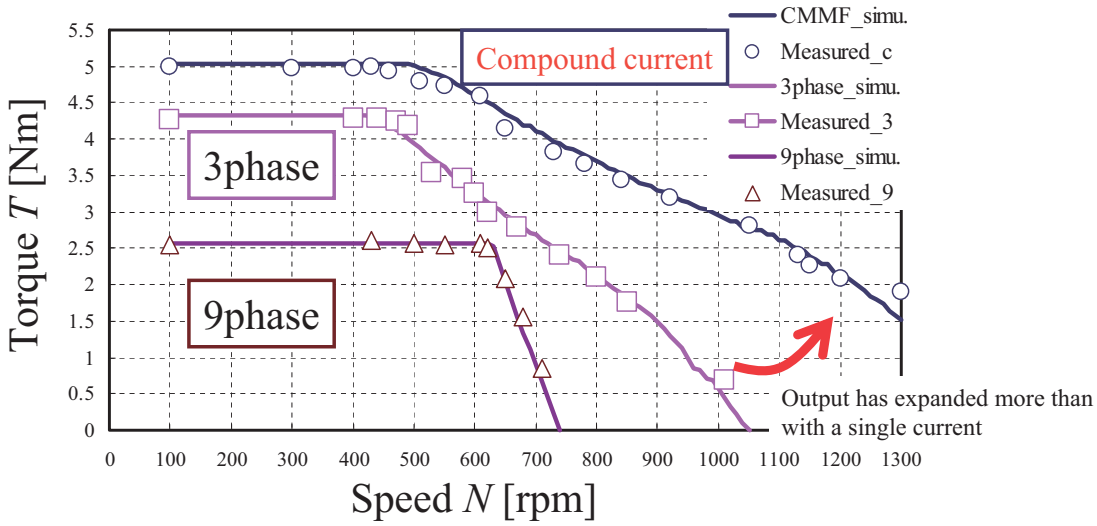
3 phase current

Compound current



・Compound current has equivalent torque with the comparison motor

d) Speed—torque characteristics

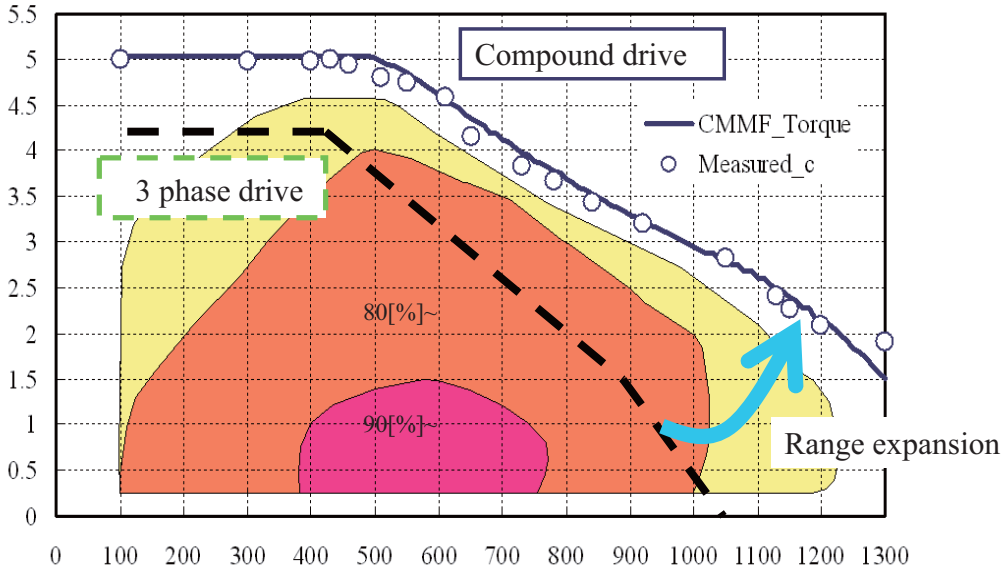


・Confirming agreement between the simulation and the actual experiment results

・We were able to expand the drive range with the compound current

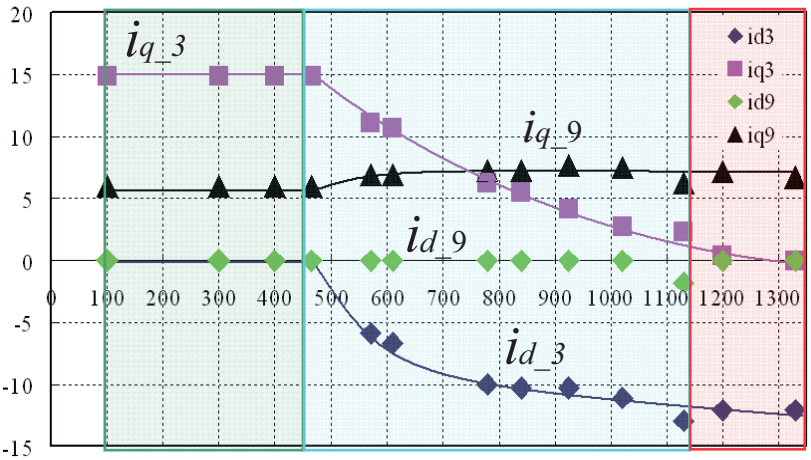
d) Compound characteristics

Simulation
Test results



・**The drive range has expanded** more than with a 3 phase current
=>Using both characteristics effectively (Weaker flux controls with a 3 phase +9 phase torque)

d) Compound characteristics- Regarding compound current reference values

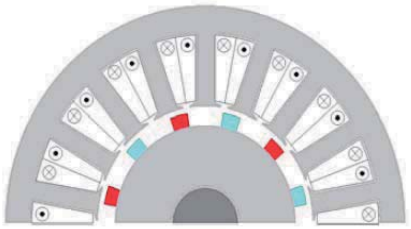


・*iq3, iq9* current (max. torque region), **compound torque**

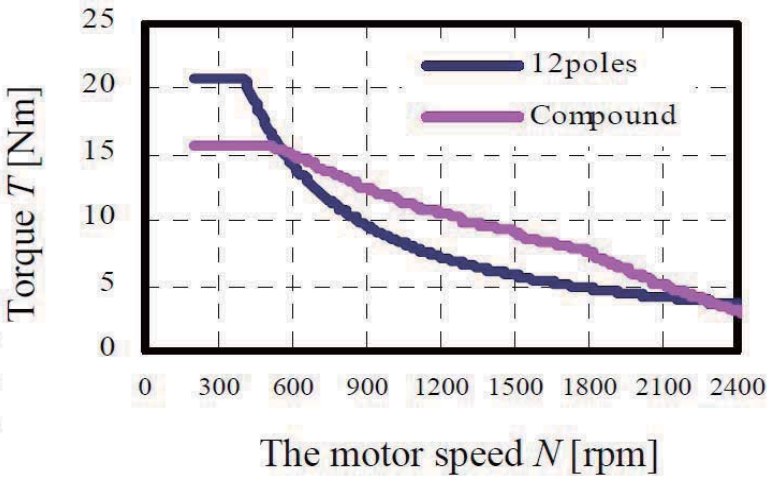
・3 phase weak flux control, **compound torque**

・3 phase weak flux control, torque output in a **9 phase**

An N-T Characteristic Comparison With a 12 Pole Magnet Equivalent Quantity Motor



Magnet flux	Φ_d [mWb]	66.9
d-axis Inductance	L_d [mH]	4.19
q-axis Inductance	L_q [mH]	4.18



- A characteristic comparison with a magnet equivalent quantity 12 pole motor
- It has the benefit of output expansion via the **9 phase current** in the mid-speed range

CMM Motor Summary

- Thanks to multi-phase drives, it has become possible to generate an appropriate rotating magnetic field, and we confirmed that we can achieve high efficiency in a broad spectrum.
- Present research
  - Changing to IPM
  - Independent drives via dual coils

In Conclusion

I. Matrix motors, which have switches that change between multiple coils

II. CMMF motors, with which it is possible to select motor characteristics thanks to multiple magnet motive forces and controls

Expansion of the drive range and high efficiency range is possible thanks to variable characteristics with a high degree of freedom

Merging with power electronics is the key for both!
Merging power electronics analysis with electromagnetic field analysis will continue to get even more important!