6-phase Fault-Tolerant Permanent Magnet Traction Drive for Electric Vehicles

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High Power Motor

Role of partners in supply chain

IFAG

USFD

VW

IGBT 650V

22 kW 22 kW
320 V 320 V

Gear ratio (8-10)

41 kW

320 V

6~

Multi-phase inverter with independent control

Fault tolerant multi-phase motor having wide speed range with high efficiency

Specifications and Workbench tests

Infineon

University Of Sheffield

ARTEMIS

ENIAC
Key challenges for EV traction

A. Starting torque at low speed
B. Acceleration
C. Efficiency
D. Speed range
E. Power density
F. Torque ripple
G. Reliability & fault tolerance
H. Flexibility of control
Drive train & design specifications

- Nominal DC link voltage: 320 V
- Maximum line-line voltage: 650 V
- Cooling medium: Water

Power train drive for segment A vehicle

![Diagram of power train drive](image)

![Graph showing torque and speed](image)

- Peak torque: 41 kW at 2800 rpm
- Continuous torque: 22 kW at 4000 rpm, 32 kW at 10000 rpm

Drive train & design specifications

[Diagram showing motor, inverters, and battery]

Motor
Inverter 1
Inverter 2
Battery
Novel fault-tolerant 6-phase electric motor

Novel 6-phase, 18-slot, 8-pole winding configuration

- **Improvement of safety and availability** by designing the machine topology as two independent balanced 3-phase systems in single stator
- **Fault tolerant** as vehicle will continue to run with 50% power/torque output even with loss of one 3-phase system
- Lower torque ripple & cogging torque
- Lower eddy current losses in rotor PMs
- Lower copper losses due to shorter end-windings
Novel fault-tolerant 6-phase motor

- Development of winding configuration

3-phase, 9-slot, 8-/10-pole winding

6-phase, 18-slot, 8-/10-pole winding
The novel winding configuration eliminates many harmonics, which leads to lower eddy current loss in PM and lower torque ripple in a machine.
## Novel fault-tolerant 6-phase motor

### Design Constraints for EV traction motor with PMs

<table>
<thead>
<tr>
<th>Type of constraints</th>
<th>Design parameter</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric</td>
<td>Stator outer radius</td>
<td>mm ≤ 75.00</td>
</tr>
<tr>
<td></td>
<td>Stack length of the motor</td>
<td>mm ≤ 150.00</td>
</tr>
<tr>
<td></td>
<td>Mass of PM material</td>
<td>kg ≤ 1.2</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Maximum flux linkage (derived from maximum line-to-line voltage)</td>
<td>mWb ≤ 74.7</td>
</tr>
<tr>
<td></td>
<td>Inductance (to achieve peak torque)</td>
<td>mH &gt; 0.256</td>
</tr>
<tr>
<td></td>
<td>Inductance (to achieve high efficiency in field weakening region)</td>
<td>mH ≤ 0.721</td>
</tr>
<tr>
<td>Thermal</td>
<td>Copper winding temperature</td>
<td>°C ≤ 180°</td>
</tr>
<tr>
<td></td>
<td>Steel lamination temperature</td>
<td>°C ≤ 225°</td>
</tr>
<tr>
<td></td>
<td>PM temperature</td>
<td>°C ≤ 150°</td>
</tr>
</tbody>
</table>
Novel fault-tolerant 6-phase motor

- Design optimized against specifications, mechanical and thermal constraints for maximum efficiency over NEDC
- Cross-section of optimized design

Conceptual design
- 1.1 kg PM material
- 94.4% energy efficiency over NEDC

Optimized design
- 0.9 kg PM material
- 94.9% energy efficiency over NEDC
### Novel fault-tolerant 6-phase motor

- **Performance of the optimized design – at rated & peak torque**

<table>
<thead>
<tr>
<th></th>
<th>Rated Torque</th>
<th>Peak Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>Nm</td>
<td>75</td>
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<tr>
<td>Torque ripple</td>
<td>%</td>
<td>2.5</td>
</tr>
<tr>
<td>Speed</td>
<td>rpm</td>
<td>2800</td>
</tr>
<tr>
<td>Peak current</td>
<td>A</td>
<td>74.0</td>
</tr>
<tr>
<td>Current density</td>
<td>A/mm²</td>
<td>9.7</td>
</tr>
<tr>
<td>Copper loss</td>
<td>W</td>
<td>809</td>
</tr>
<tr>
<td>Iron loss</td>
<td>W</td>
<td>181</td>
</tr>
<tr>
<td>PM eddy current loss</td>
<td>W</td>
<td>8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>95.7</td>
</tr>
<tr>
<td>NEDC energy efficiency</td>
<td>%</td>
<td>94.9</td>
</tr>
</tbody>
</table>

#### Graphs
- **Rated torque & Peak torque**
- **Rotor angle (elect. deg)**
- **Speed, rpm**
- **Torque, Nm**
- **NEDC energy efficiency**
Novel fault-tolerant 6-phase motor

Prototype motor & inverter

- Laminations
- Stator frame
- Stator assembly
- Rotor assembly
- Motor assembly
- Inverter with instrumentation
Novel fault-tolerant 6-phase motor

- Test bench for direct measurement of efficiency at USFD
Novel fault-tolerant 6-phase motor

- Comparison of prediction and test results at USFD

- The measured back EMF matches very well with the finite element analysis predictions with a difference being just 2.7%.

- The efficiency at the base speed of 2800 rpm matches closely with the prediction.
Novel fault-tolerant 6-phase motor

- Measured efficiency map of inverter & motor with 320V at VW

- Both the inverter and the motor exhibits high efficiency over the wide speed range.
Novel fault-tolerant 6-phase motor

- Measured efficiency map of power drive train at VW

- The novel fault-tolerant motor-inverter drive system has a high efficiency over wide speed range.
Conclusions

- Novel 6-phase motor is designed and developed to enhance safety and availability of power train drive.
- The motor is inherently fault tolerant. Loss of one 3-phase system does not result into complete loss of traction power.
- The new motor configuration exhibits high efficiency over a wide speed range, which is one of the key requirement for EV traction.
- Series of experimental measurements on a prototype motor and inverter have validated the novel fault-tolerant motor.