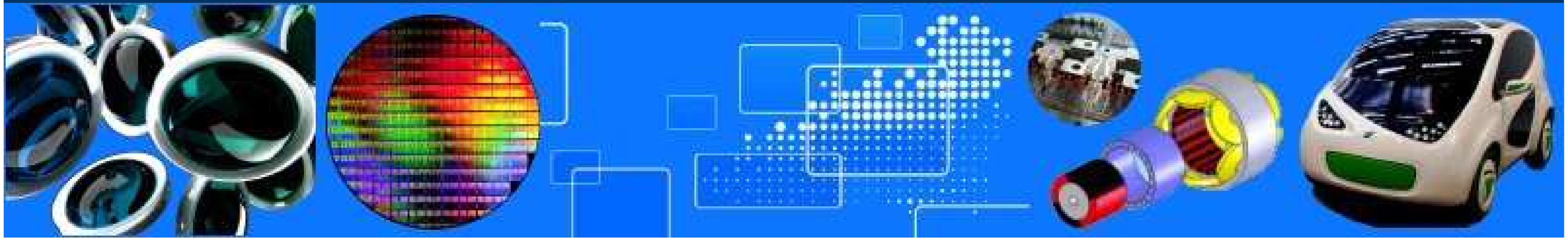


Nano-Electromobility
University of Seville, Seville, Spain, 1st February 2012

CASTOR
Car Multi Propulsion Integrated Power Train

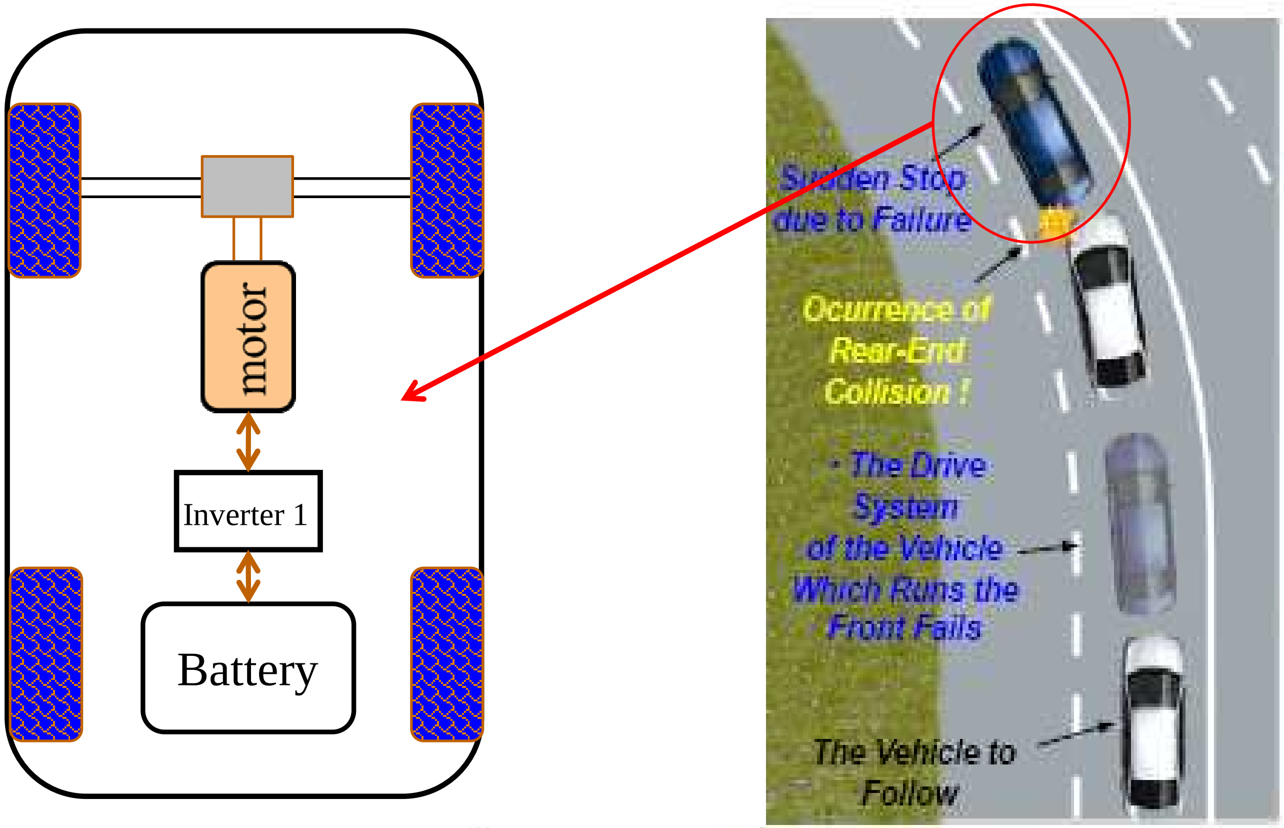
CAr multi propulSion integraTed pOwer tRain

Multi-phase motor and propulsion concepts

Jiabin Wang, The University of Sheffield, UK
Jonas Tousen, Volkswagen AG, Germany

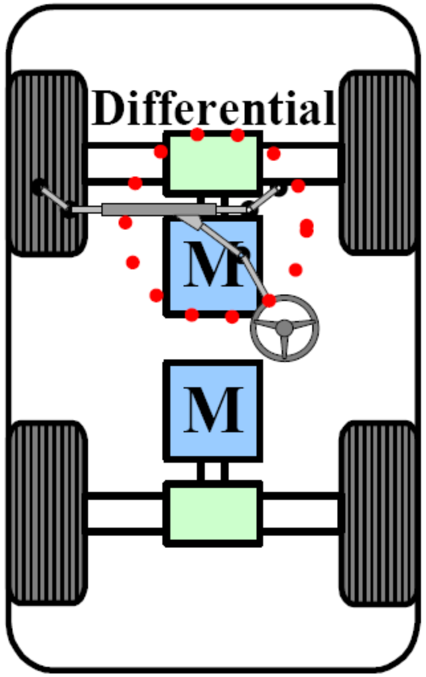
Safety implication of single drive EVs

- Failure of any key component in single drive EV power train may result in a serious accident

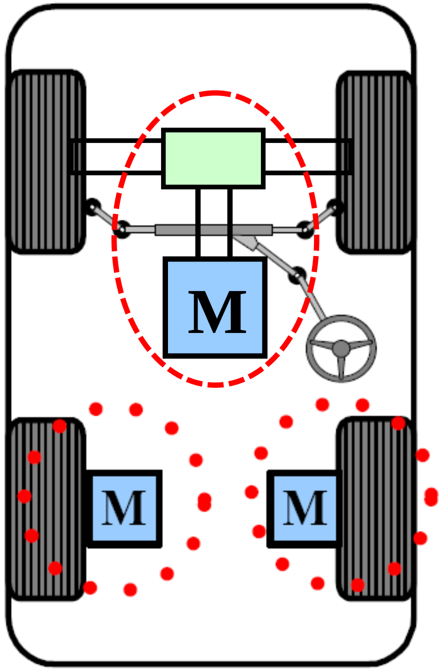


Fail-safe, distributed EV power trains

- Front and rear drives via two differentials

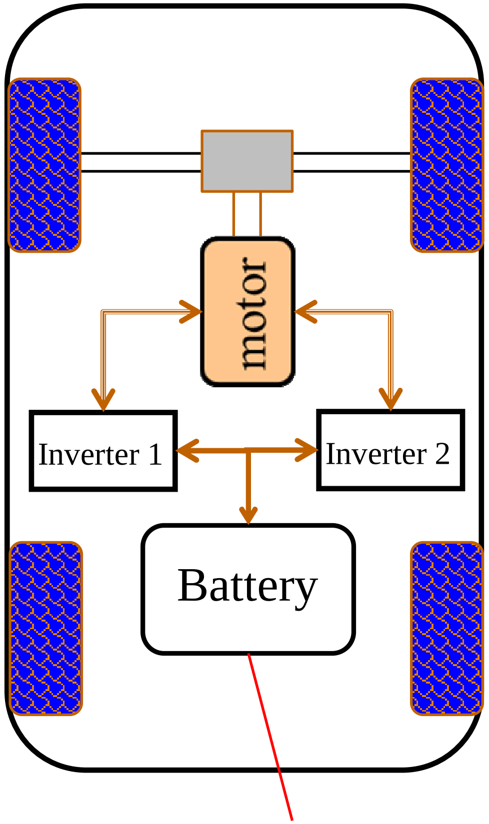


- Front drive via differential with two independent rear drives



- Loss of power in any single drive will not lead to complete loss of propulsion. The cost of implementation is of concern

Multi-phase motor propulsion concept

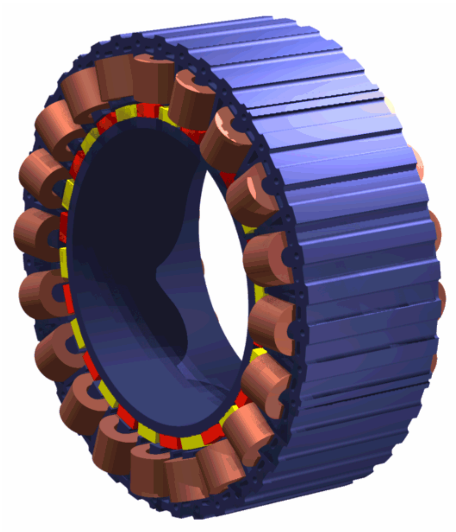


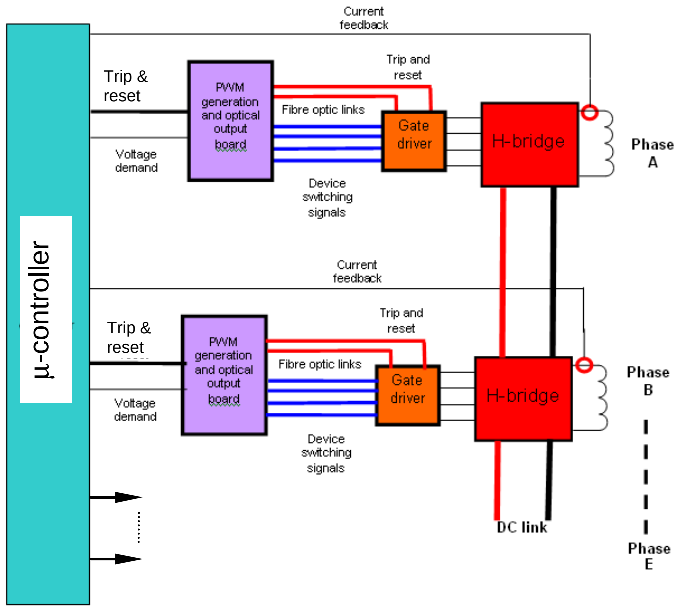
- Single motor power train architecture for ease of mechanical integration and thermal management
- Motor winding is configured to have a number of independent groups of phases
- Each group of phases is controlled by independent inverter
- This provide a degree of redundancy and modularity as well as reduced inverter rating

Battery may also be separated

Multi-phase machine and drive topology

- Each phase is physically, magnetically, thermally and electrically isolated

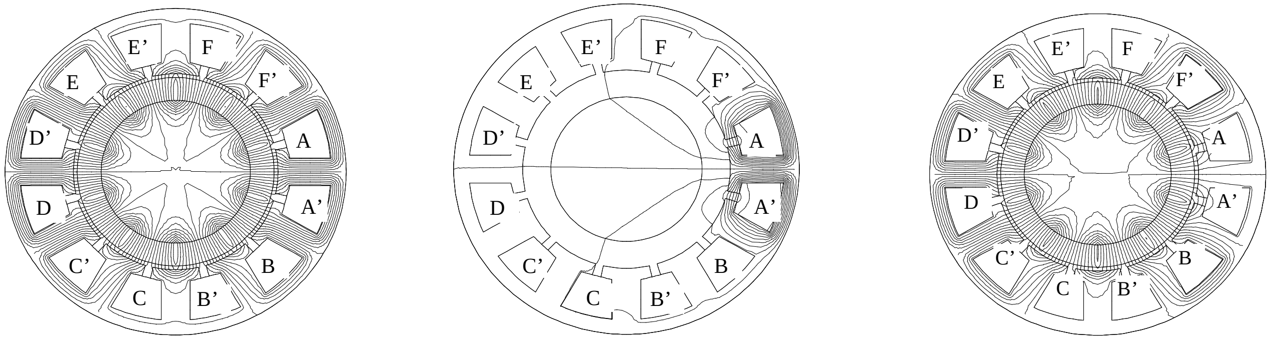




- Fault-tolerant philosophy also extends to the drive:
  - Each motor phase supplied from individual H bridge, which is physically and electrically independent to limit possibility of fault propagation
  - Control logic diagnoses machine and converter faults, and in the event of a short-circuit or open-circuit, safely shuts down faulted phase and modifies drive operation

Fault-tolerant PM machines

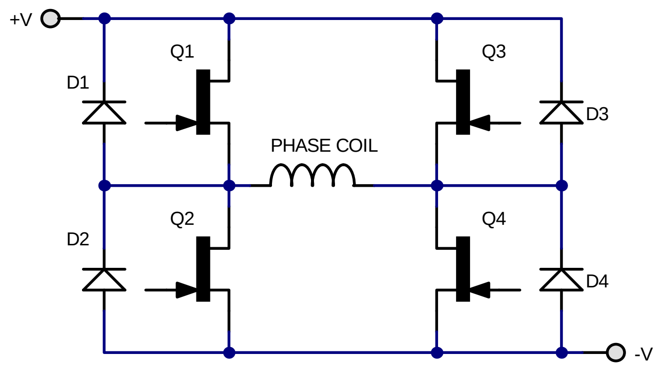
- Magnetic field distribution



Open-circuit Phase A excited Phase A short-circuited

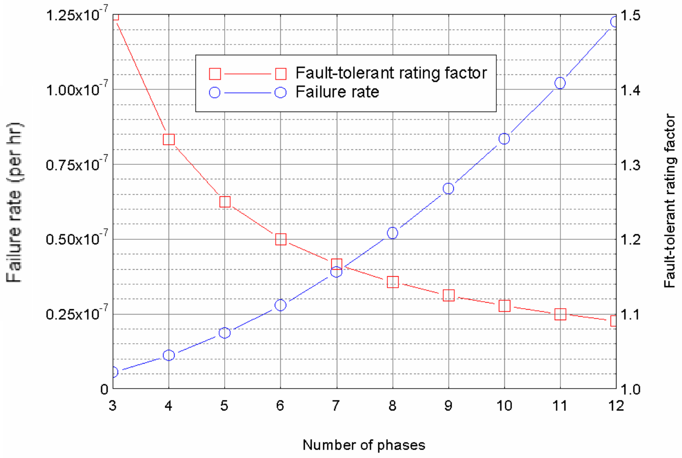
6-phase, 12-slot, 10-pole machine

- Negligible mutual coupling between phases
- Short-circuit across phase winding has negligible effect on flux linking other phases
- If the phase reluctance is 1pu, the machine is fault-tolerant, ie. it can operate indefinitely with a short-circuited phase since the short- circuit current is limited to rated full-load value

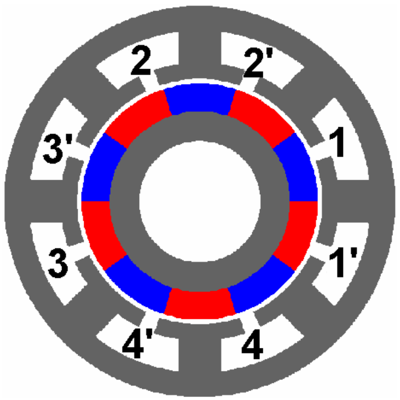


Fault-tolerant PM machines

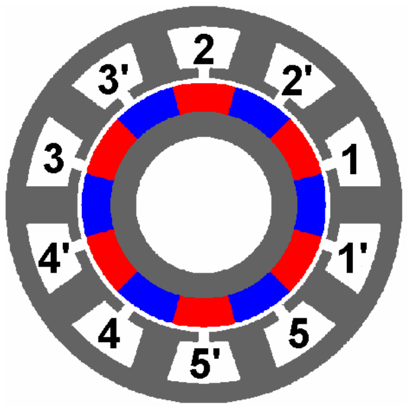
- Number of phases affects failure rate and over-rating requirement



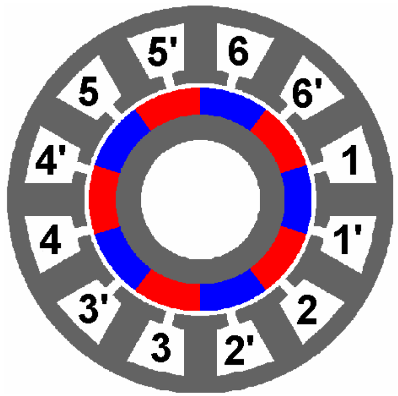
- Low phase number improves reliability, but introduces slight size penalty



4-phase, 8-slot, 10-pole



5-phase, 10-slot, 12-pole
Rated torque: 21.8Nm



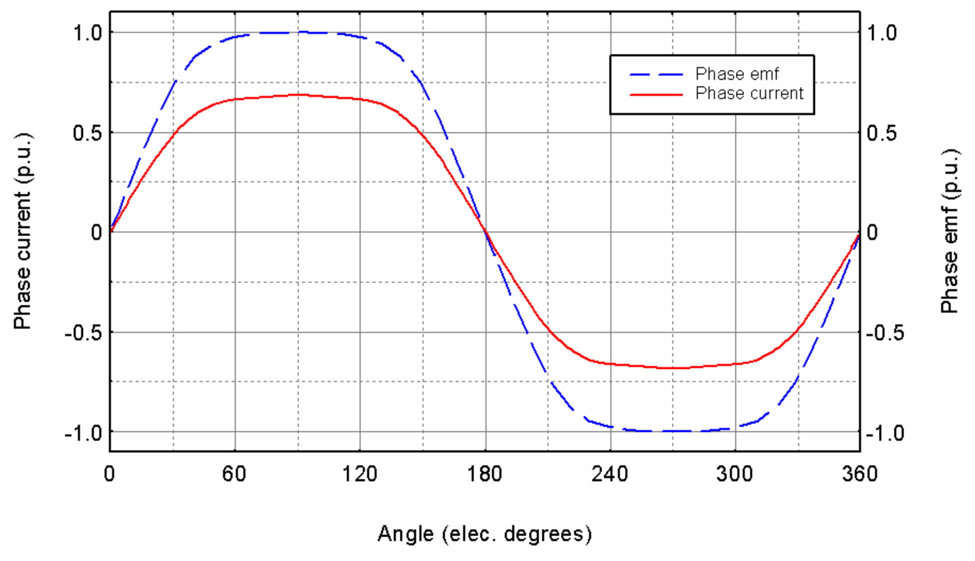
6-phase, 12-slot, 10-pole

Optimal torque control

➢ To minimise torque ripple (and copper loss) under both healthy and fault conditions

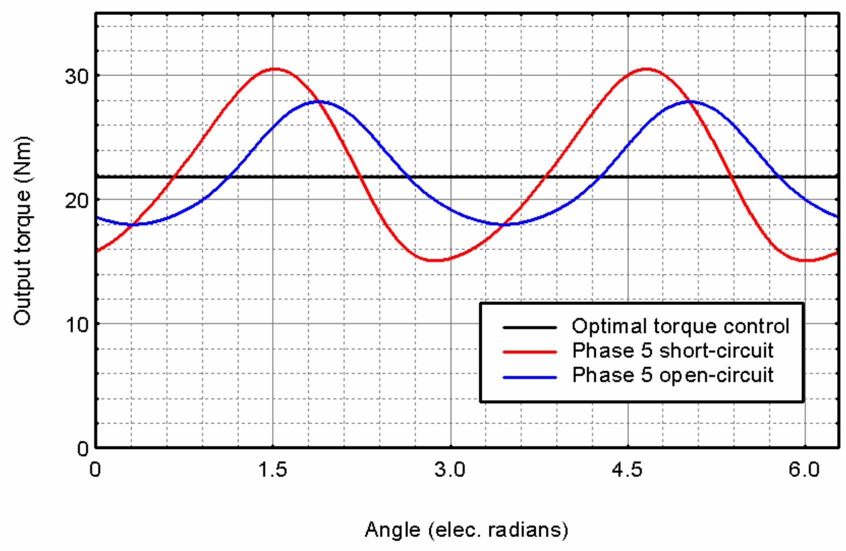
5-phase, 12-pole, 10-slot modular machine

➢ Optimal phase current waveform for a healthy machine with zero torque ripple



▪ Current expressed as a per unit of rated emf and load current

➢ Electromagnetic torque waveforms when unfaulted phases supplied with optimal current waveform for healthy machine

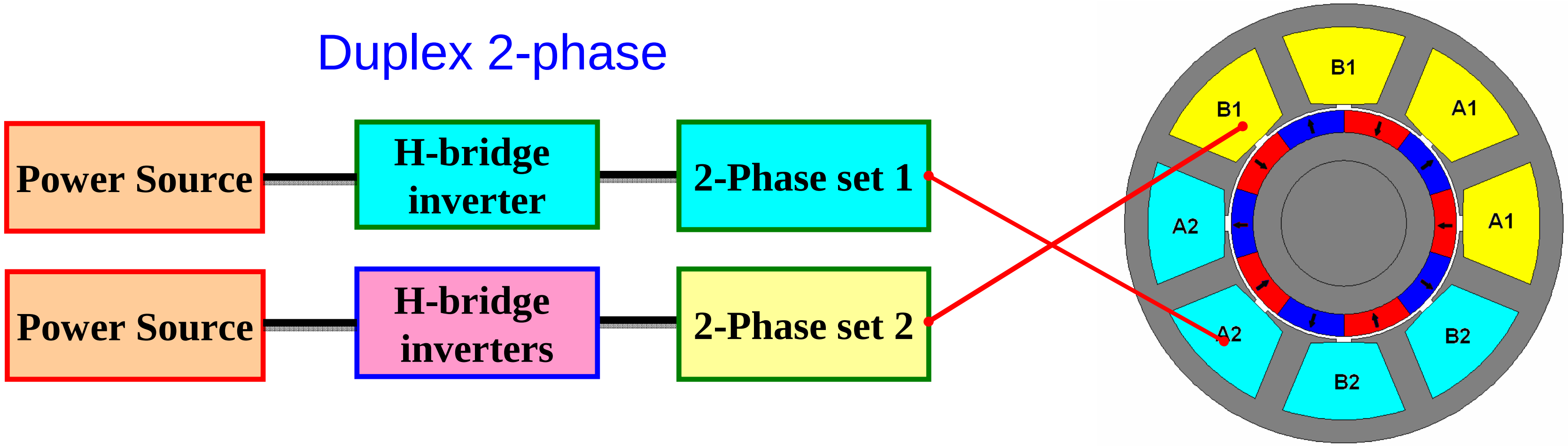


▪ Significant torque ripple results when a phase is either open-circuited or short-circuit

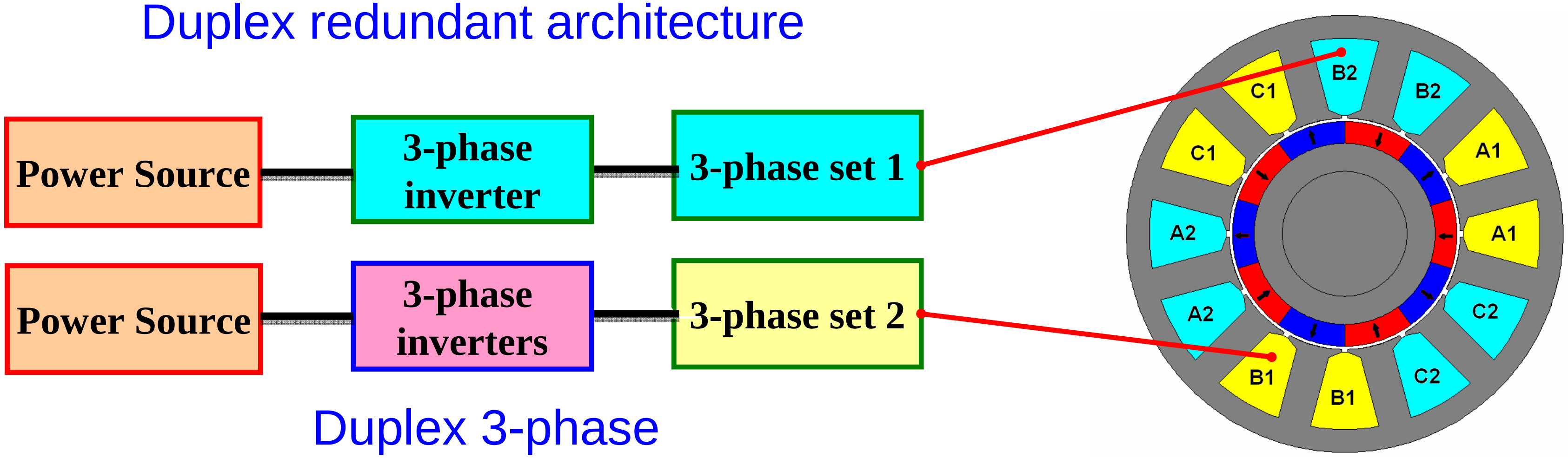
Fault-tolerant PM machines

Multiplex 2- & 3-phase Fault-tolerant PM machines

Duplex 2-phase



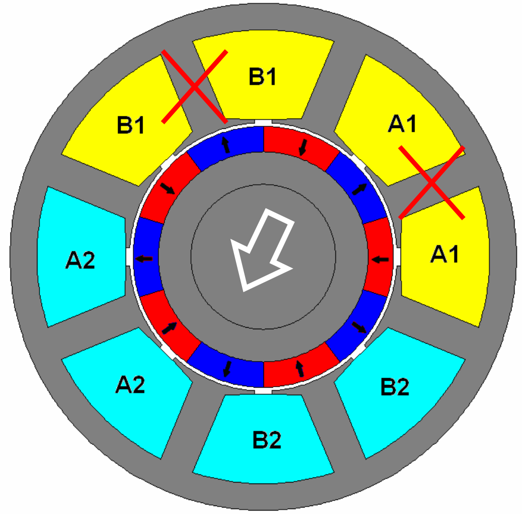
Duplex redundant architecture



Duplex 3-phase

Performance comparison

- 2-phase design has unbalanced magnetic pull if one set of 2-phase winding is out of service under a fault condition
  - Noise and vibration
  - Additional eddy current loss in the magnets
- No such problem for 3-phase design if one set of winding is out of service



- **Converter VA ratings**

H-bridge converters for 2-phase machine $V_{rms2} = V_{dc} / \sqrt{2}$

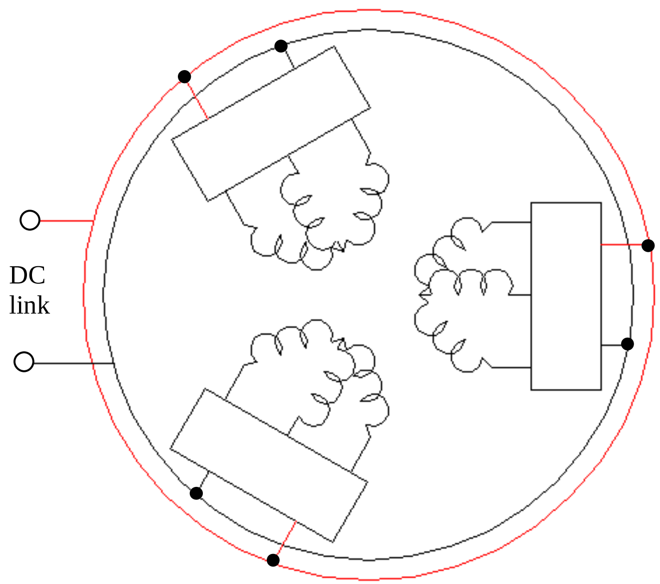
Space vector modulation used for 3-phase inverter $V_{rms3} = V_{dc} / \sqrt{6}$

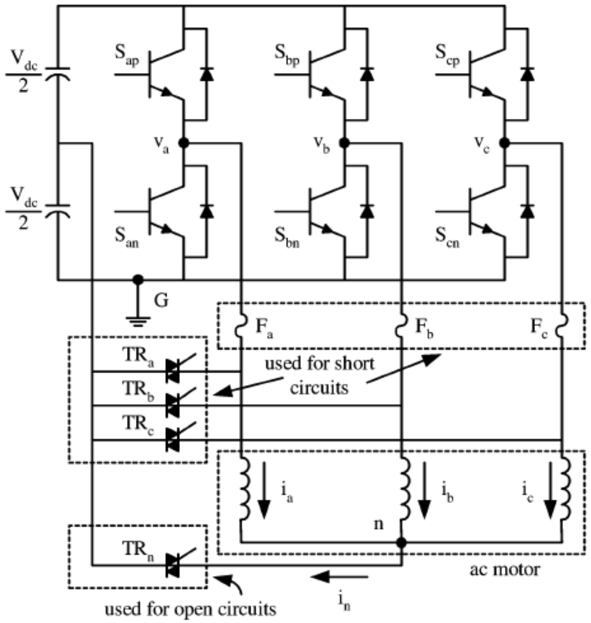
For the same apparent input powers $I_{rms3} = (2/\sqrt{3}) I_{rms2}$

$$\frac{\text{3-phase inverter } 6V_{dc} \times I_{rms3}}{\text{2-phase inverter (2 H-bridges) } 8V_{dc} \times I_{rms2}} = \mathbf{0.866}$$

3-phase triplex motor drive

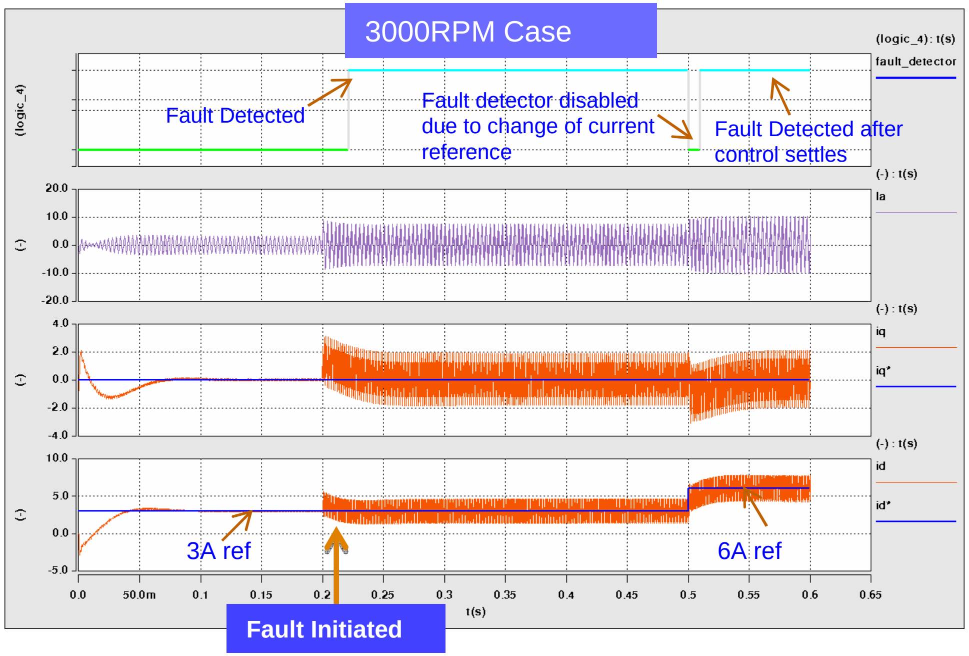
- Multiplex 3-phase system is more cost-effective
- Each 3-phase inverter can incorporate tolerant functions which allow continuous two-phase operation in the events of one phase open- or short-circuit faults

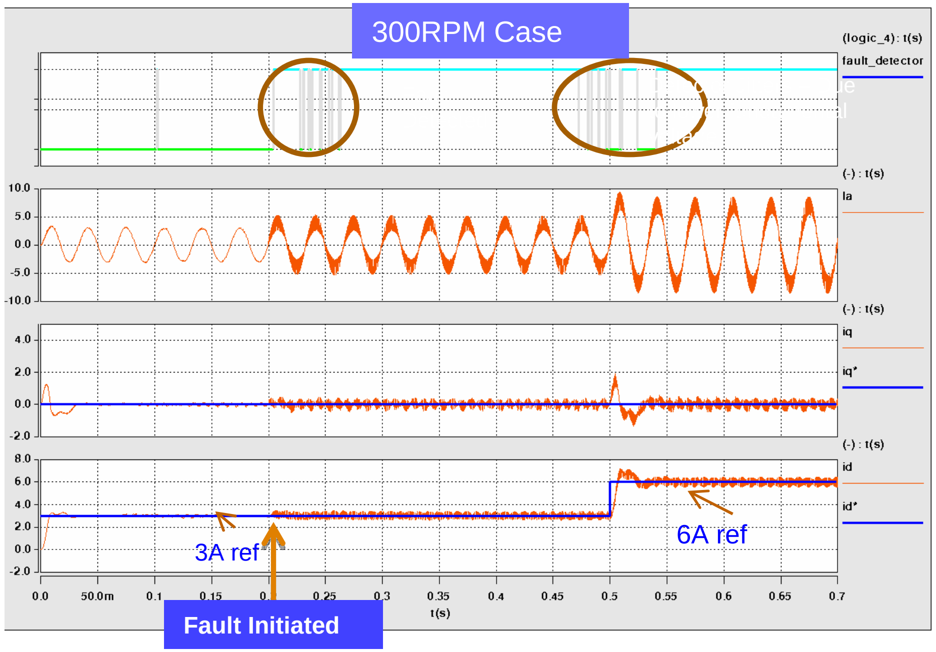




Fundamental frequency based fault detection

- Transient model (Saber)





Discussion

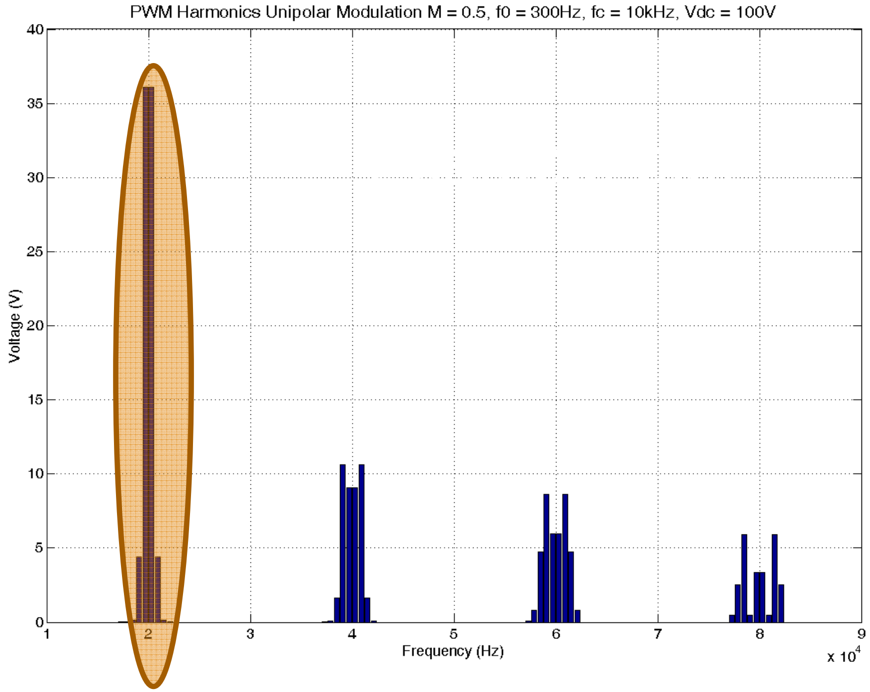
- Single phase inverter with Unipolar modulation (10kHz). Dead-time = 1us. Inverter Dead-time compensated using [1].
- Prelim results of Terminal fundamental voltage based fault detection
- As speed reduces, the voltage error is less and therefore susceptible to noise issues.

High Frequency based technique

Current PWM Harmonics

$$i_{ph} = \frac{8V_{dc}}{\pi} \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{Z_{mn}} \frac{1}{2m} J_{2n-1}(m\pi M)\cos([m+n-1]\pi)\cos(2m\omega_c t + [2n-1]\omega_0 t)$$

Z_{mn} changes due to turn faults



Where,

- M = Modulation Index
- Wc = Carrier frequency (rad/sec)
- W0 = Fundamental frequency (rad/sec)
- Vdc = ½ of full DC link voltage

- ‘m’ corresponds to carrier frequency multiples
- ‘n’ corresponds to fundamental frequency (sideband) components

- Only first carrier harmonic and its sidebands considered for calculation HF RMS current because of the bandpass filter, i.e,
- ‘m’ = 1; n=[-4:1:4]

Skin effect Resistance Scaling

$$Rh = R_{f_0} * \sqrt{\frac{f_h}{f_0(=300Hz)}}$$

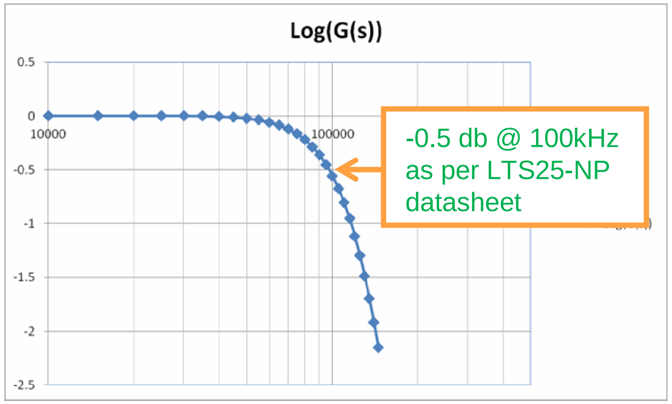
High Frequency Response to Turn Fault

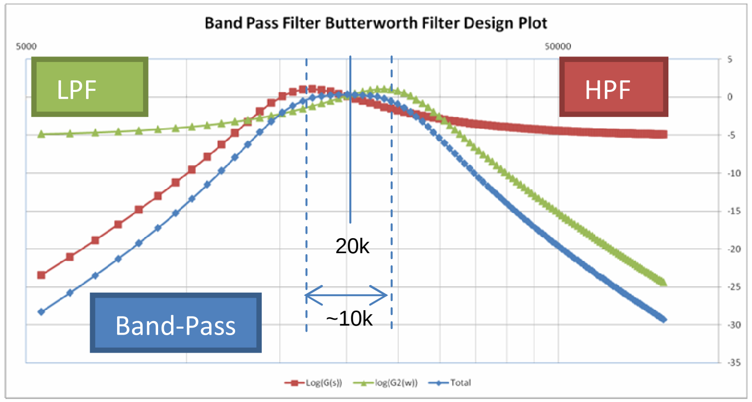
- **Transient Simulation (skin effect not modelled)**

Signal Flow Chain

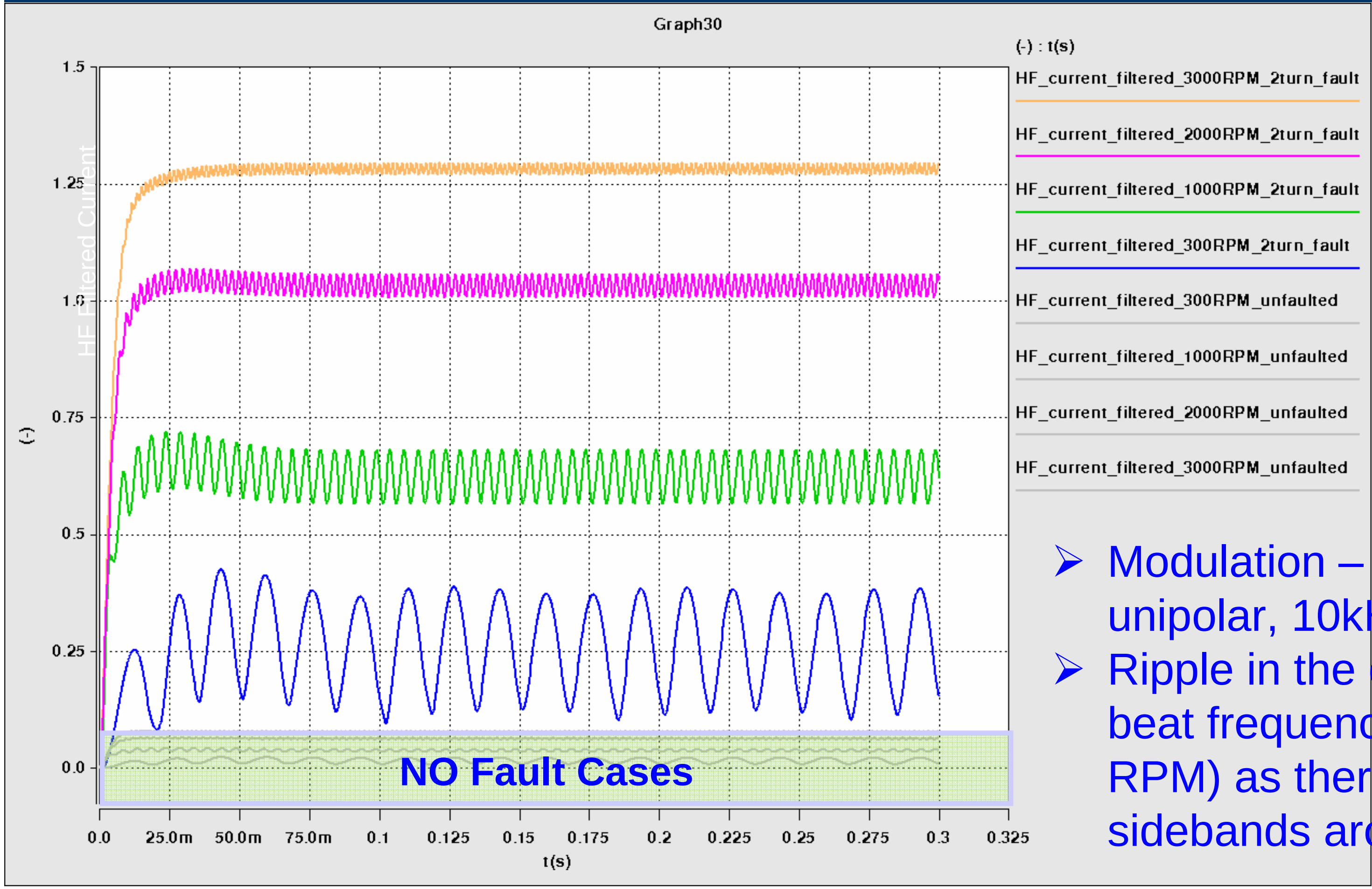
Phase Current → **LEM Model** → **Band-Pass Filter model** → **Ideal Rectifier** → **LPF** → HF Filtered Current

- LEM Model: 100kHz BW of LEM Sensor
- Band-Pass Filter model: 20kHz centre Freq, 10kHz Band-pass Butterworth 4th order
- Ideal Rectifier: ABS(x)
- LPF: 2nd order filter





High Frequency based fault detection



- Modulation – sine-triangle, unipolar, 10kHz
- Ripple in the output is due to beat frequency (function of RPM) as there are 2 PWM sidebands around 20kHz

- Filtering can be improved
- Results shown is without compensation algorithm

EVs - A Way of Life - A New Lifestyle

Enjoy Life!

Emissions -> **Electrical vehicle vs. combustion vehicle:**

CO: -99%, **HC**: -97%, **NOx**: -92%, **CO_2**: -50%