The Low Cost Auxiliary Power Unit Project (LowCAP)

Simulation of dynamic torque ripple in an auxiliary power unit for a range extended electric vehicle

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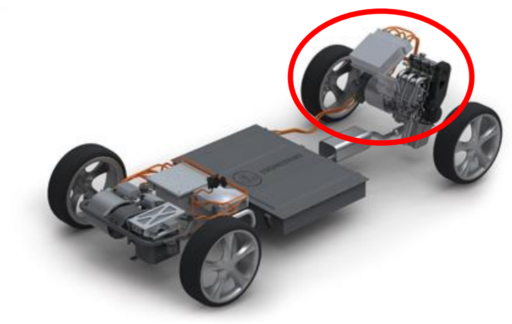
Introduction

- A range extended electric vehicle (REEV) gives zero pipe emission for daily short commute and capability for occasional long distance trip.

- An auxiliary power unit (APU) in the REEV is the power generating unit to maintain the battery state of charge.



- An APU usually equipped with a low-cylinder-count engine which suffers more significant in-cycle torque fluctuation and thus speed oscillation and NVH

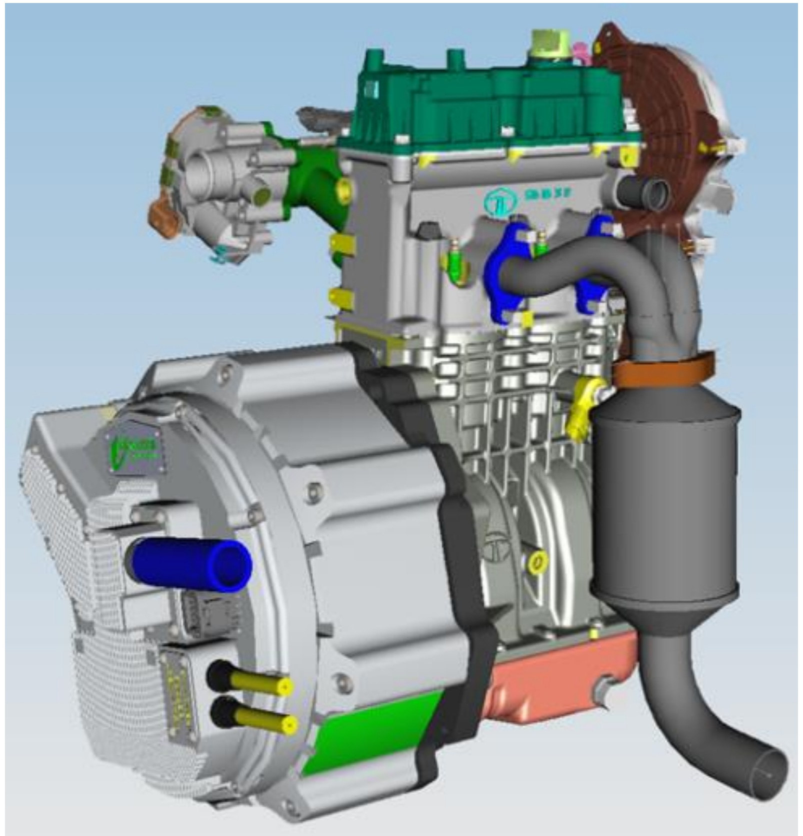
- As the electric generator could directly coupled to the crankshaft and with the help of active rectifier (PWM inverter), there is potential to dynamically control the electric machine torque output to counteract the engine in-cycle torque.

Picture from http://www.theengineer.co.uk/in-depth/range-extender-engines/1008736.article

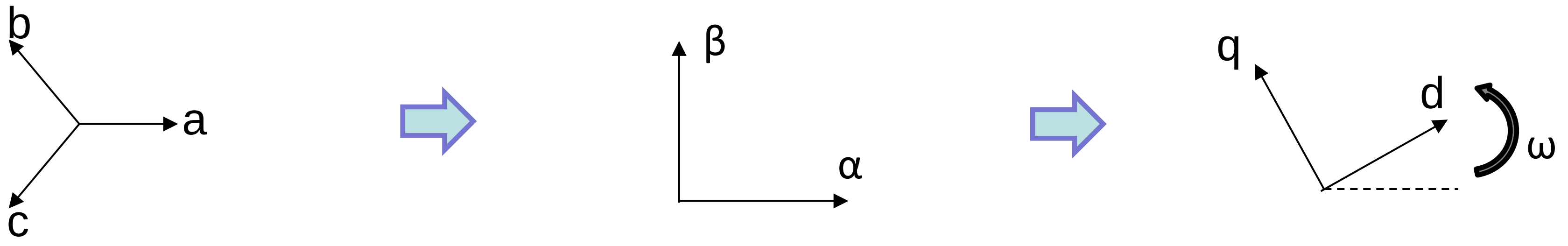
Target system

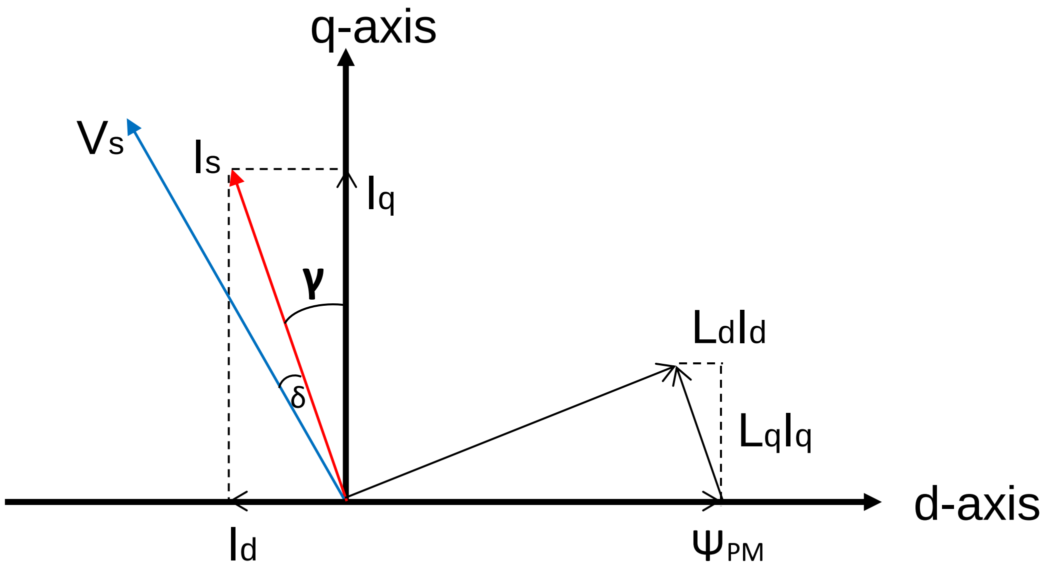
- Interior permanent magnet (IPM) generator
- Rated generator torque is 62Nm
- DC bus voltage 350 – 400V

- 0.6L twin cylinder NA engine
- Peak engine torque is 51Nm @ 4000rpm
- The target APU system electric power output is 20-23kW between 4000 to 5000rpm



Electric machine dq control





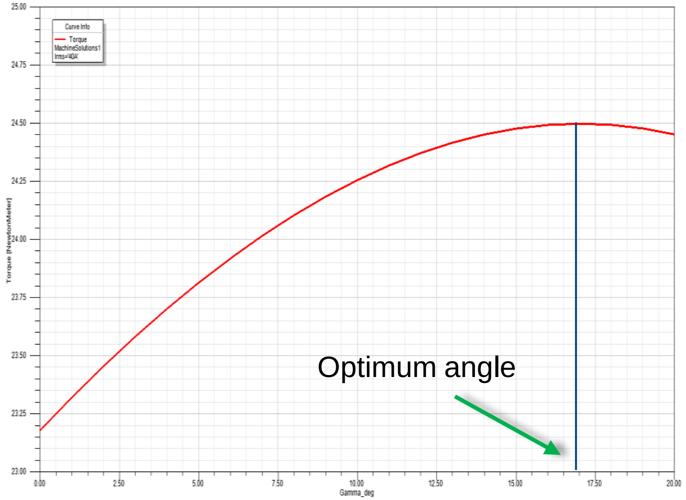
$$I_s = \sqrt{{I_d}^2 + {I_q}^2}$$

$$\tan\gamma = {}^{I_q}\!/_{-I_d}$$

Electromagnetic torque and torque angle (γ)

$$T_e = \frac{3}{2} \cdot npp \cdot (\psi_{pm} \cdot I_q + (L_d - L_q) \cdot I_d \cdot I_q)$$

$$T_e = \frac{3}{2} \cdot npp \cdot (\psi_{pm} \cdot I_s \cdot \cos\gamma - (L_d - L_q) \cdot {I_s}^2 \cdot \sin\gamma \cos\gamma)$$

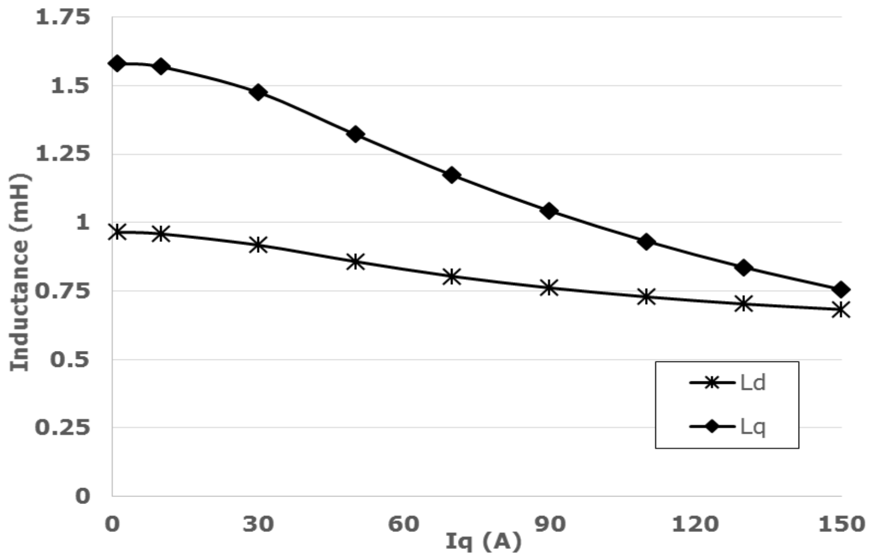


for I=40A

$$\gamma = \sin^{-1}\left(\frac{\psi_{pm} + \sqrt{{\psi_{pm}}^2 + 8(L_d - {L_q}^2){I_s}^2}}{4(L_d - {L_q}^2)I_s}\right)$$

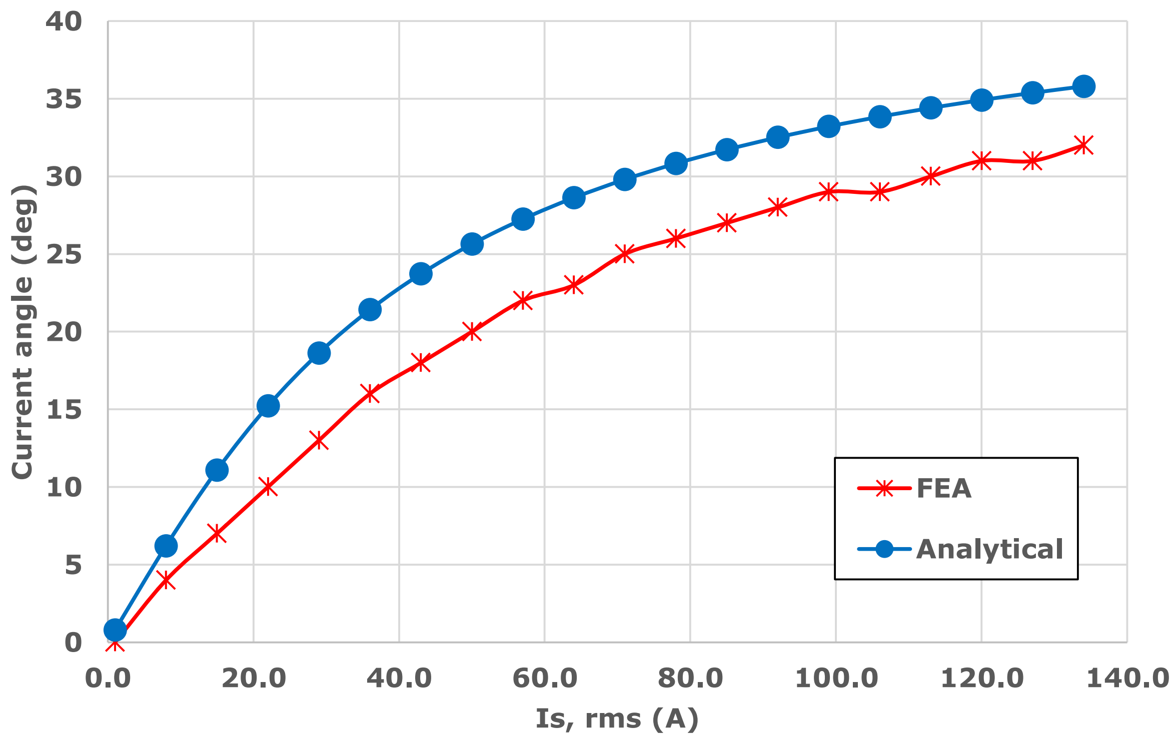
Winding inductance variation

- As current increases and thus the flux density, the stator iron may starts to saturate.
- Therefore, the dq-axis inductances vary under different load conditions and it results in different optimum torque angle.



FEA results for γ=0

Torque angle results



- The figure shows how the optimum torque angle changes against load current.
- When inductance variation is not considered, the angle will be overestimated.

Analytical model with data from FEA

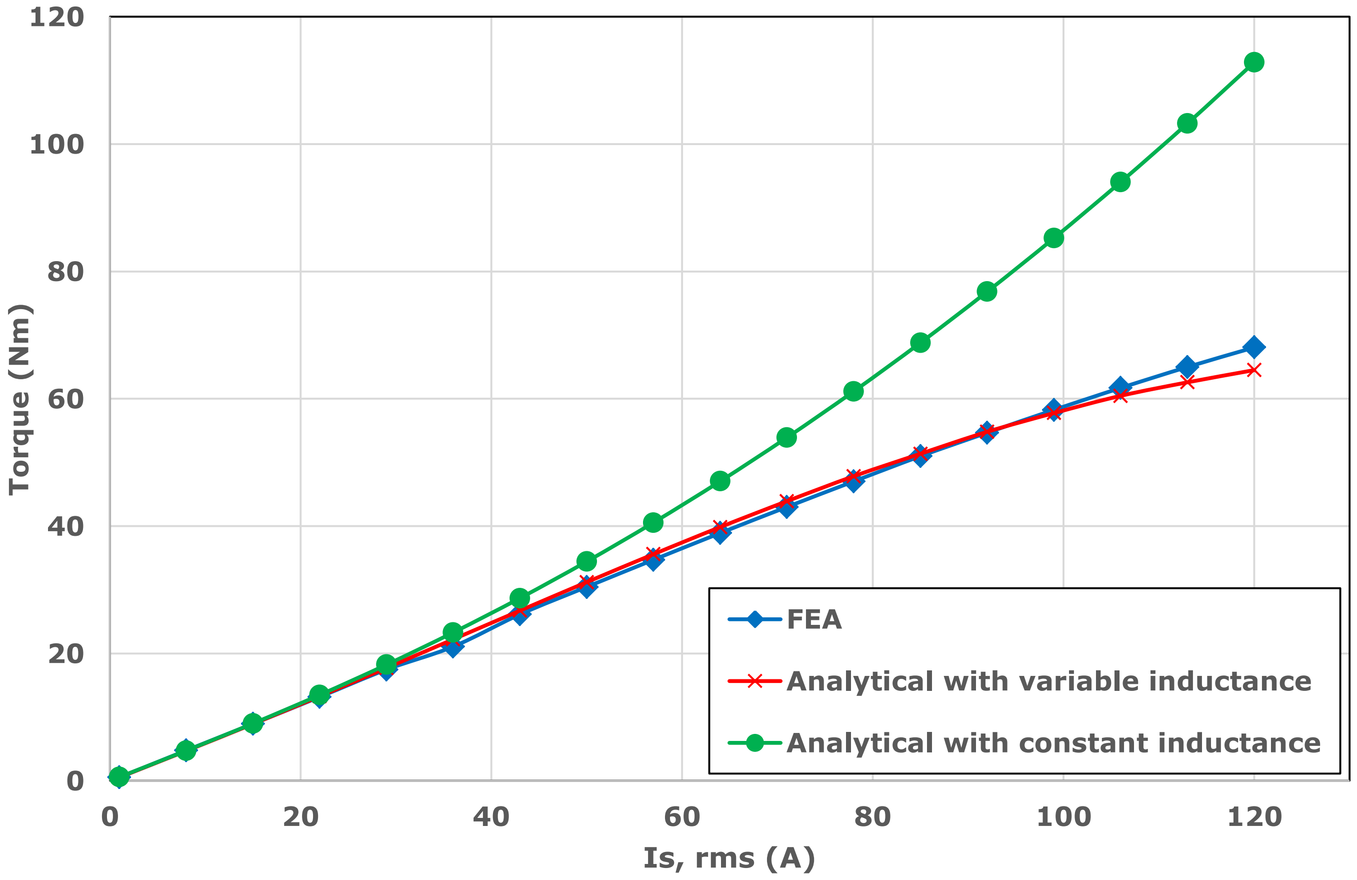
- Finite element analysis (FEA) model can give accurate results, but the simulation time is long and too slow to do in-cycle control.

- The analytical electric machine is very fast to run but usually with constant winding inductance values. To increase the model performance accuracy, the inductance and torque angle data are stored in tables and used in the analytical model.

- The results shows a good match to the electric machine performance FEA results comparing to constant inductance analytical model.

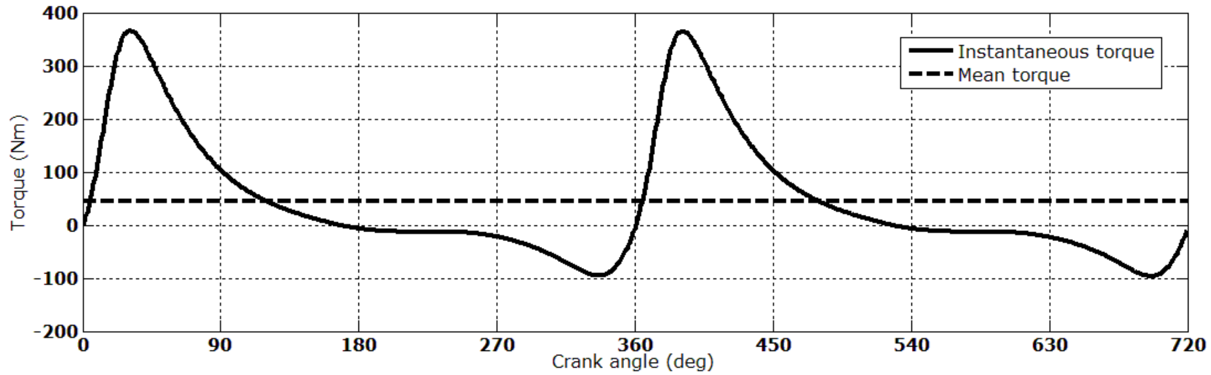
- However, the model is not able to predict the machine losses and thermal behaviour. This is a trade off between computation time and model accuracy.

Analytical model with data from FEA

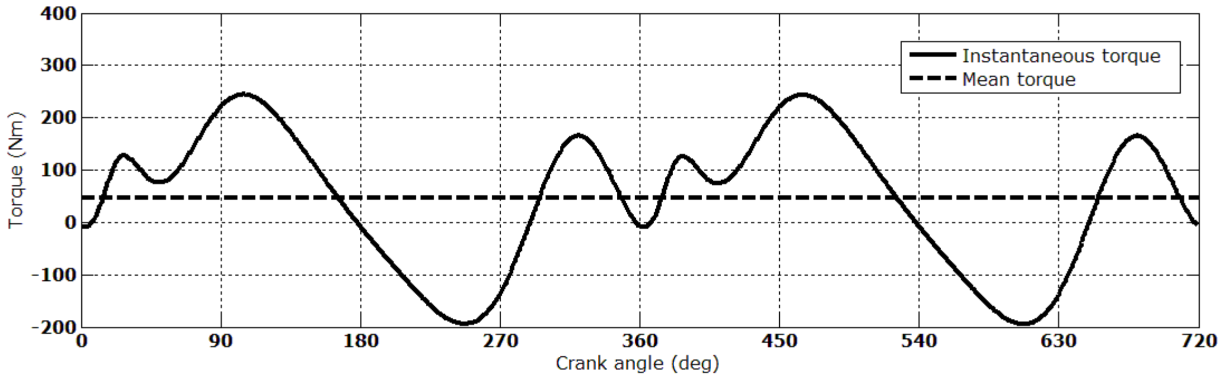


APU dynamic torque control

- The engine in-cycle torque pattern (4500rpm):

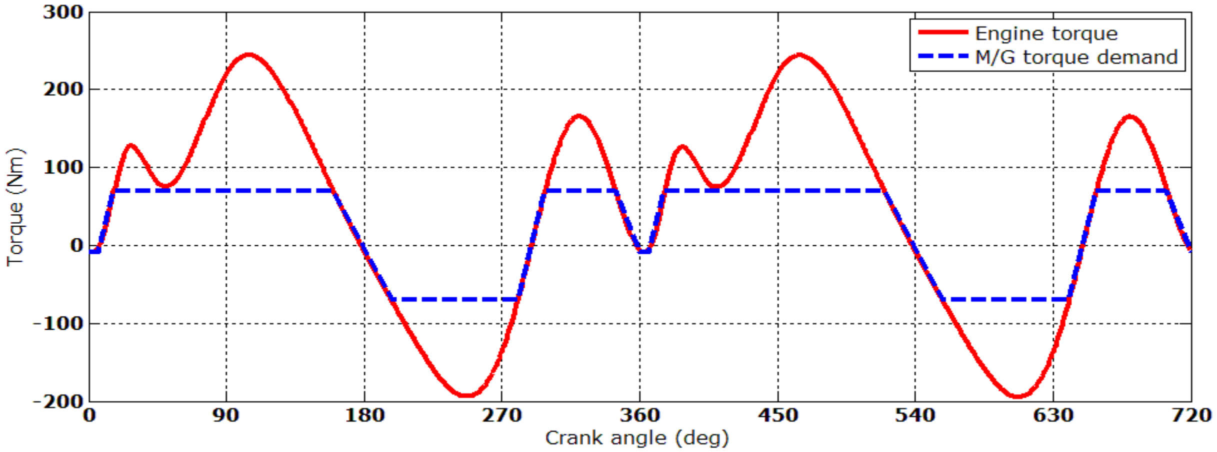


- In-cycle torque with rotating inertia considered (4500rpm):



APU dynamic torque control

Initial active torque proposal for the generator – following the engine torque closely

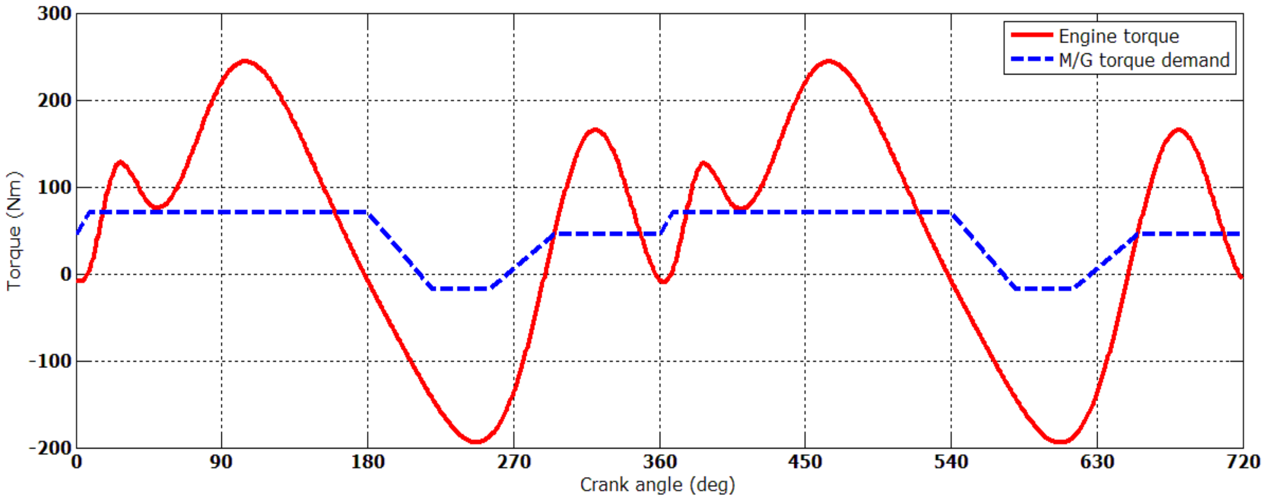


* *To give a clear view of the M/G torque, the torque demand curve is mirrored around x-axis.*

- The average generator torque is lower than the engine's. This means not all of the mechanical power will be converted into electricity.
- An additional braking source is needed to hold the engine speed.
- This is not practical for APU application.

APU dynamic torque control

Modified active torque pattern for the electric machine – matching the average torque of the generator and the engine

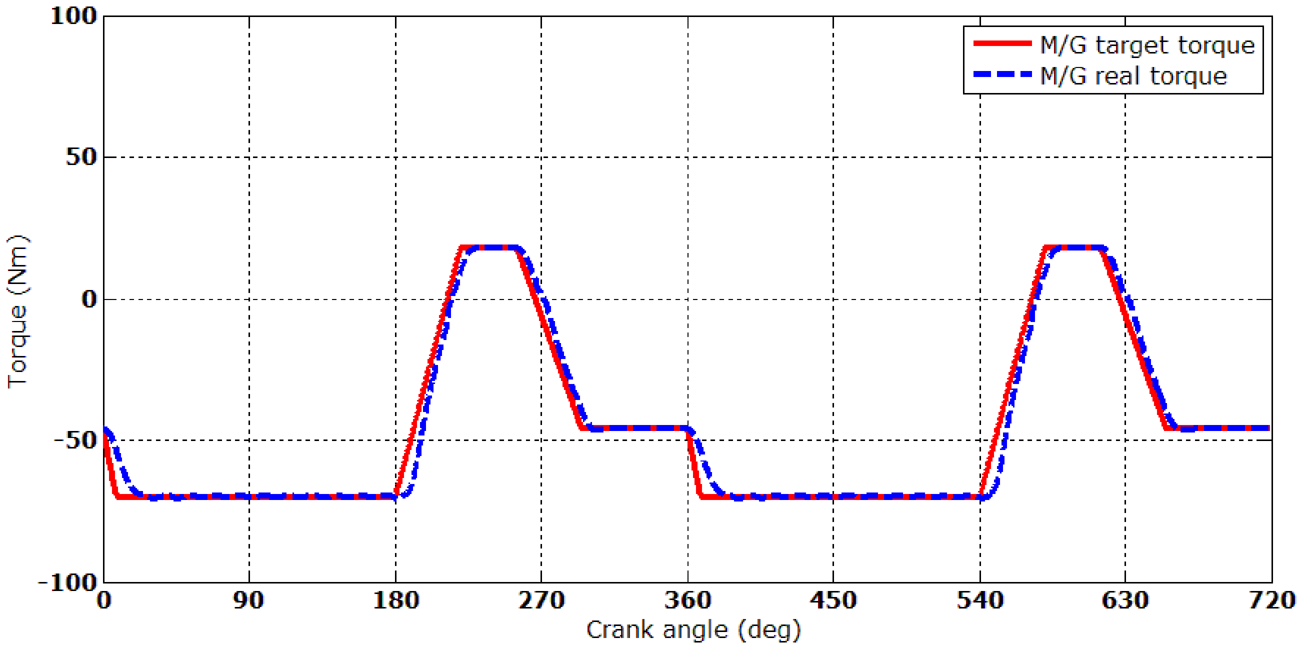


* *To give a clear view of the M/G torque, the torque demand curve is mirrored around x-axis.*

- Longer generating period and lower motoring torque.
- The slope of torque ramp change is reduced to make PI controller easier to stabilise for the fast in-cycle variation.

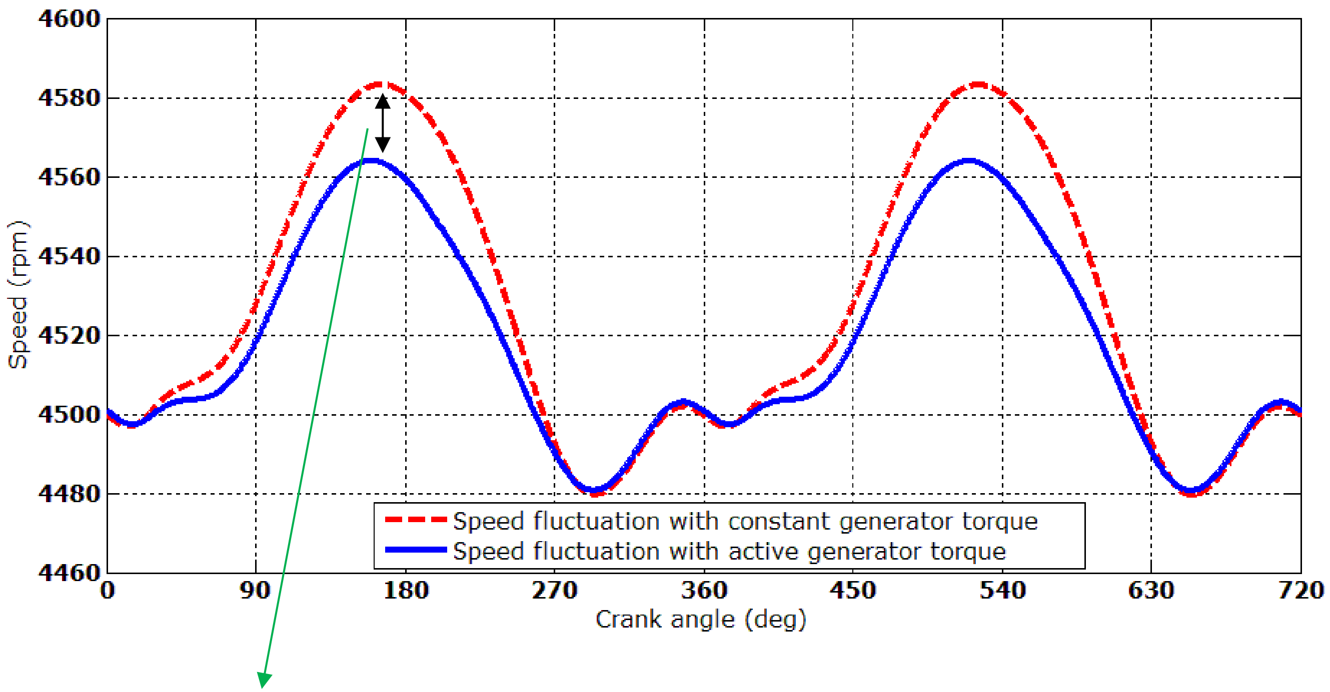
APU dynamic torque control

The simulation results of the generator torque performance under dynamic torque control.



APU dynamic torque control

The simulation results of the speed fluctuation reduction with dynamic torque control.



The peak speed oscillation is reduction by 22.9%.

Conclusion

- The FEA tool provides the ability to predict the electric machine winding inductance variation under different load conditions. But it needs long simulation time.

- With the help of FEA model data, an analytical electric machine model is developed which provides comparable performance results while reduces a large amount of running time.

- This model is used in the APU system with dynamic torque control strategy which makes the electric machine alter between generating and motoring modes to counteract with engine in-cycle torque oscillation.

- The simulation results shows that while the APU generates designated quantity of electric power, the speak speed fluctuation is improved with the dynamic torque control strategy.

Further work

- Assess the electric machine loss condition when apply dynamic torque control strategy in the FEA model and validate the results with test bench data

- Thermal behaviour of the electric machine needs to be investigated when the rapid in-cycle demand variation applied

- Alternative control algorithm, such as efficiency oriented strategy, will be studied for overall system performance evaluation

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Thank you !

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