engineexpo2009

Powertrain – Engine & transmission developments

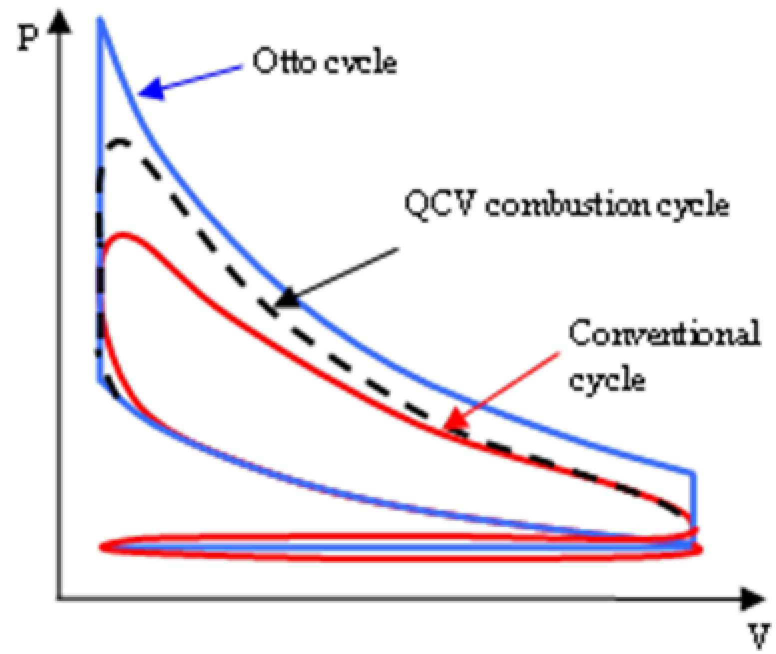
Quasi-Constant Volume (QCV) Spark Ignition Combustion

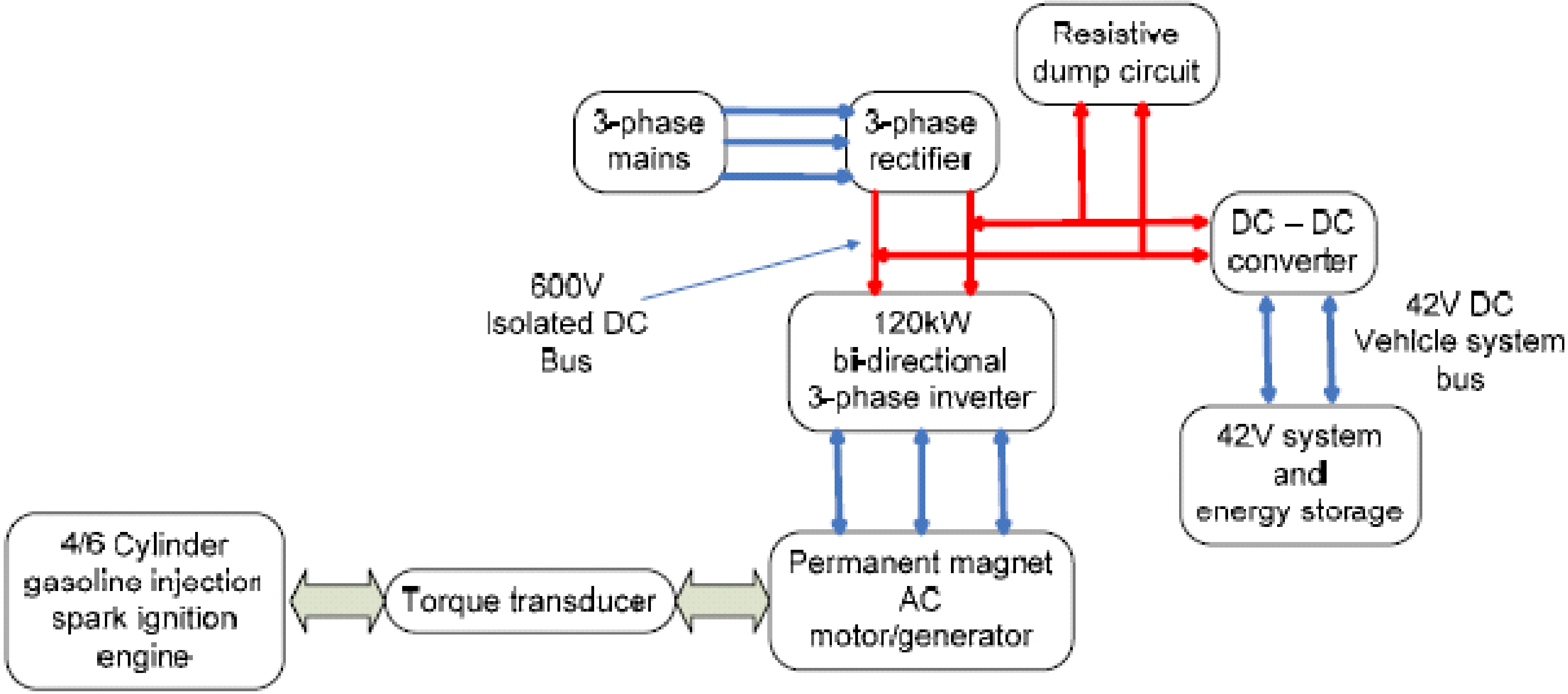
Dr. Rui Chen
Department of Aeronautical and Automotive Engineering,
Loughborough University

INTRODUCTION

- Conventional ICEs are based on a crank-rod-slider mechanism, which provides a relatively simple solution to achieve a thermodynamic cycle to produce mechanical power.
- In theory, the most efficient thermodynamic cycle for IC engines is the Otto cycle, in which the constant volume heat addition is essential for high efficiencies.
- In reality, neither conventional SI nor CI, or even the newly developed HCCI or CAI combustion processes, can achieve the efficiency level suggested by the ideal thermodynamic cycles.
- The main difficulties are due to the geometric cycle of the piston movement and the requirement that the engine delivers smooth rotation to the mechanical clutch and vehicle transmission.

- The ideal scenario is to initiate and complete the combustion event while the piston remains at the TDC position.
- A practical method is to reduce the engine crank rotation velocity at the TDC position to provide extra time for completing the combustion.
- This will then generate a new combustion cycle, Quasi-Constant Volume (QCV), which sit between conventional IC engine combustion cycle and ideal Otto constant volume combustion cycle.





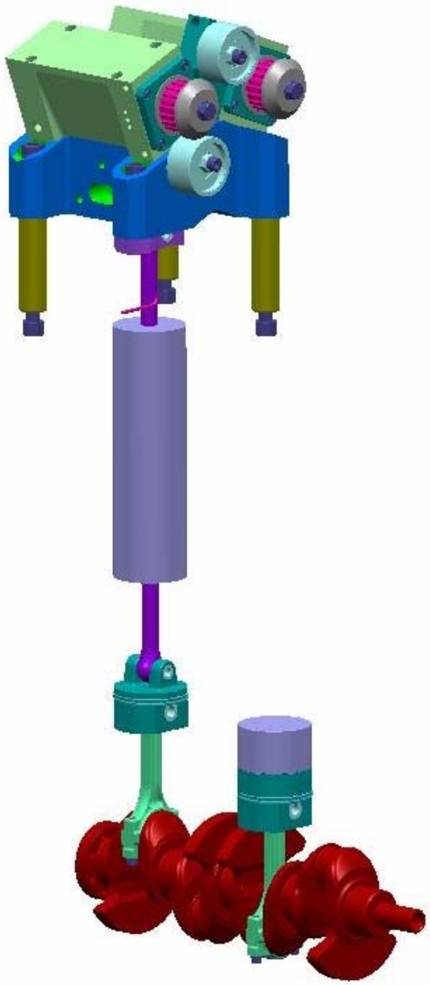
- QCV concept can be combined with a sophisticated combined electric motor and generator unit to form a series-hybrid powertrain.

PROOF-OF-PRINCIPLE

- Proof-of-concept system consists of
  - a high torque-to-inertia, high bandwidth, permanent magnet brushless AC (PMAC) electric machine,
  - a single-cylinder research Spark Ignition (SI) engine, and
  - a control system.

The Engine

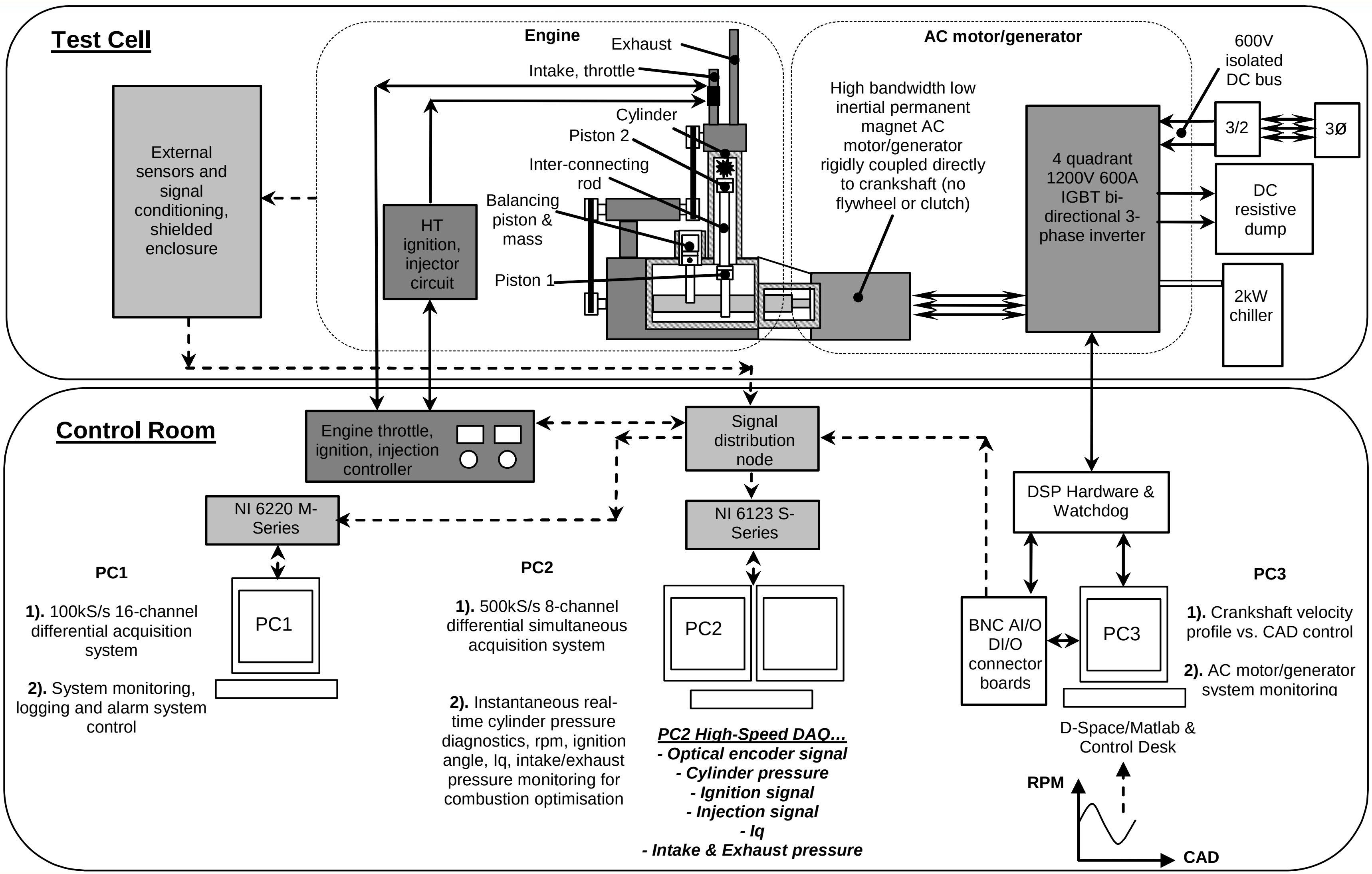
- The single cylinder research engine is based on GM Family One 1.8 litre engine architecture
- 4-valve
- bore of 80.5mm
- stroke of 88.2mm
- The bottom part is converted from a twin-cylinder engine block



Motor / Generator and Control

- The engine was attached directly at the end of the crankshaft to a 200Nm, low inertia, permanent magnet brushless AC servo-motor.
- The electric machine acts as a generator during the IC engine power stroke and as a control motor when necessary during the inlet, exhaust and compression strokes.
- The input/output power of the motor/generator controls the crankshaft trajectory at all times, so that various crankshaft angular rotation velocities can be realized and the electrical power generation to be achieved.
- Real-time engine management and electrical machine control was via a DSpace hardware.
- Direct Torque Control (DTC) which directly controls the flux and the electromagnetic torque by establishing a relationship between torque, flux and optimal inverter switching is implemented.

The QCV System and Test Rig



Fired Run Preparation/Configuration…

Controller

Driver Circuit

Crankshaft Encoder

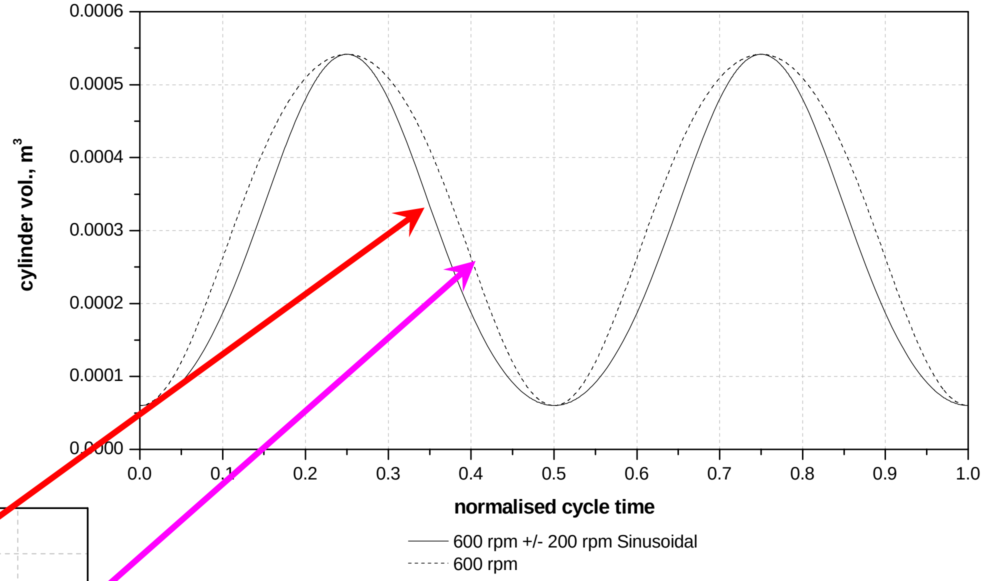
Cam Phase Optical Pick-up

Overview of New FPE Ignition/Injector/Throttle Controller…

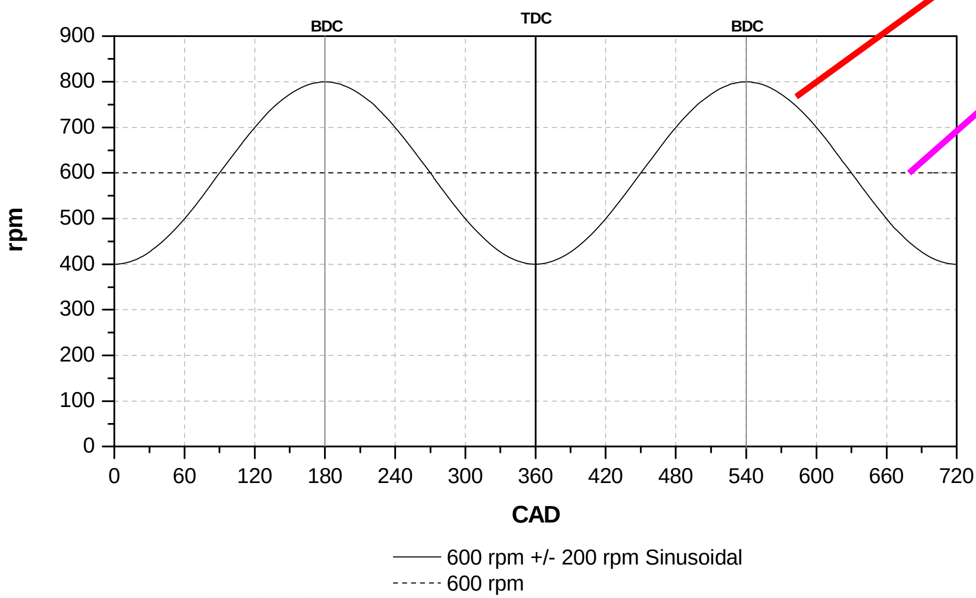
- A hardware based system was chosen rather than software for reliability and was designed and manufactured at Loughborough University (July-September 07)
- Significantly cheaper than AVL 4210 instrument controller yet provides equivalent levels of functionality
- Uses a 0.5 deg CA encoder fitted to the engine crankshaft to continuously monitor crankshaft position (camshaft phase is input via an optical pick-up)
- Toggle switches provide separate isolation for the ignition and fuel systems
- Incorporates emergency stop for engine and electric motor system shutdown

Piston Trajectory

- Sinusoidal crank rotation speed delivers a rather different piston movement profile.
- The residual time at TDC has been significantly extended, while the residual time at BDC is reduced.
- This offers longer time for the combustion event.



Cylinder volume at normalized cycle time with conventional and QCV cycles



Conventional constant and variable sinusoidal crank velocity

Electric Power

- In the d-q model of the PMAC motor, the stator currents are transformed into an orthogonal frame of reference which is moving synchronously with the rotor flux. The orthogonal reference frame is derived from the phase currents via the nonlinear transform

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} =$$

$$\frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

- The system voltage drops in the synchronous frame are given as

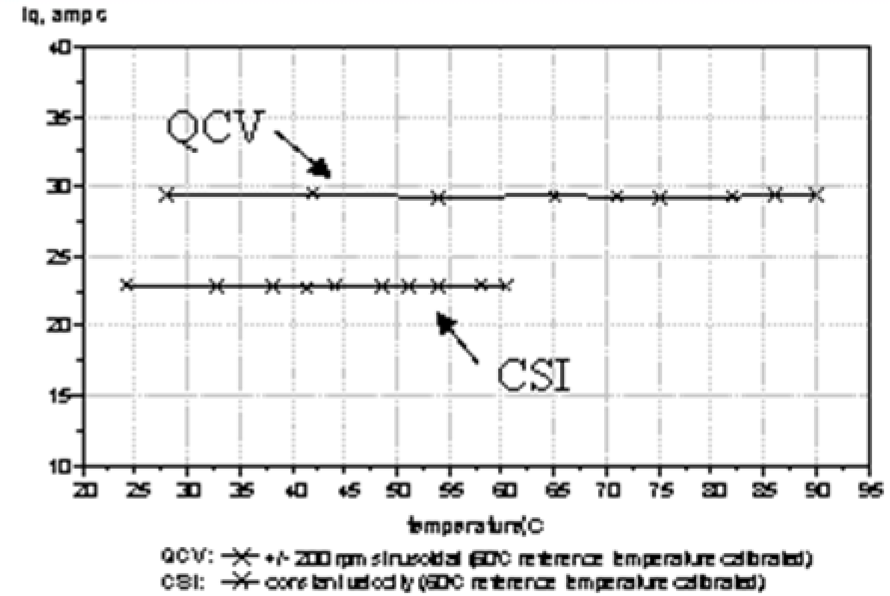
$$V_q = ri_q + \omega L i_d + \omega\kappa + L\left(\frac{di_q}{dt}\right) \qquad V_d = ri_d - \omega L i_q + L\left(\frac{di_d}{dt}\right)$$

- The electrical torque developed by the motor is proportional to the q-axis current

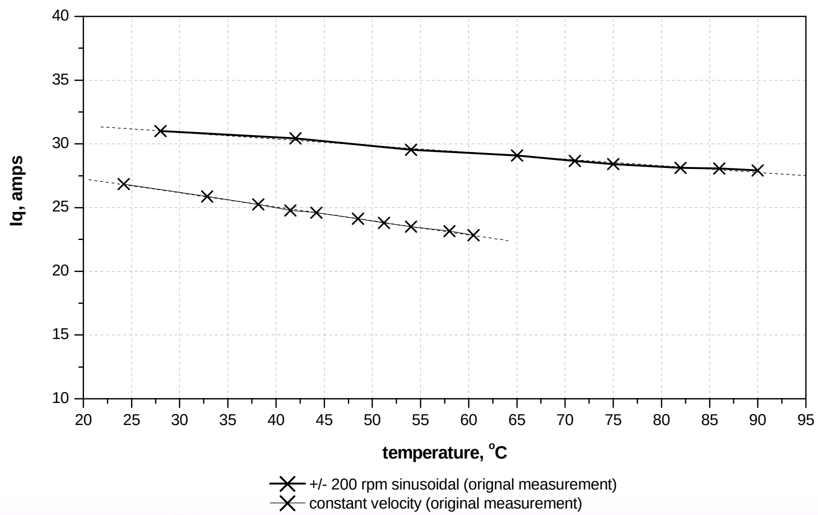
$$T_e = k_t i_q$$

Thermal Calibration

- The temperature significantly influences the electric conductivity of the materials used in the electric motor.
- The currents were calibrated to the value at 60ºC.
- The current required to motor the engine in the conventional cycle is much less, 6 amps lower than that in the QCV cycle.

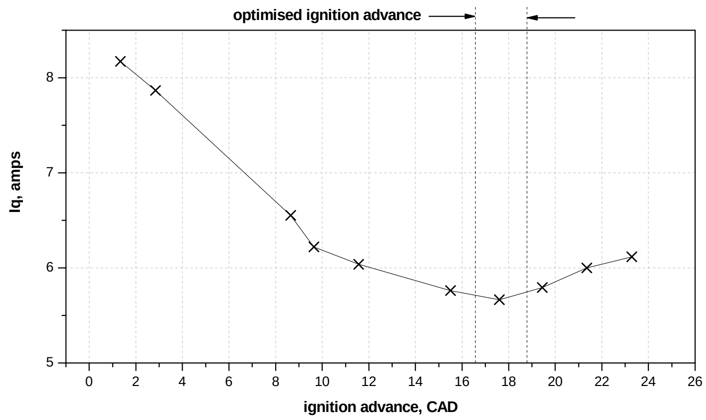


Corrected motor current at varying operation temperature

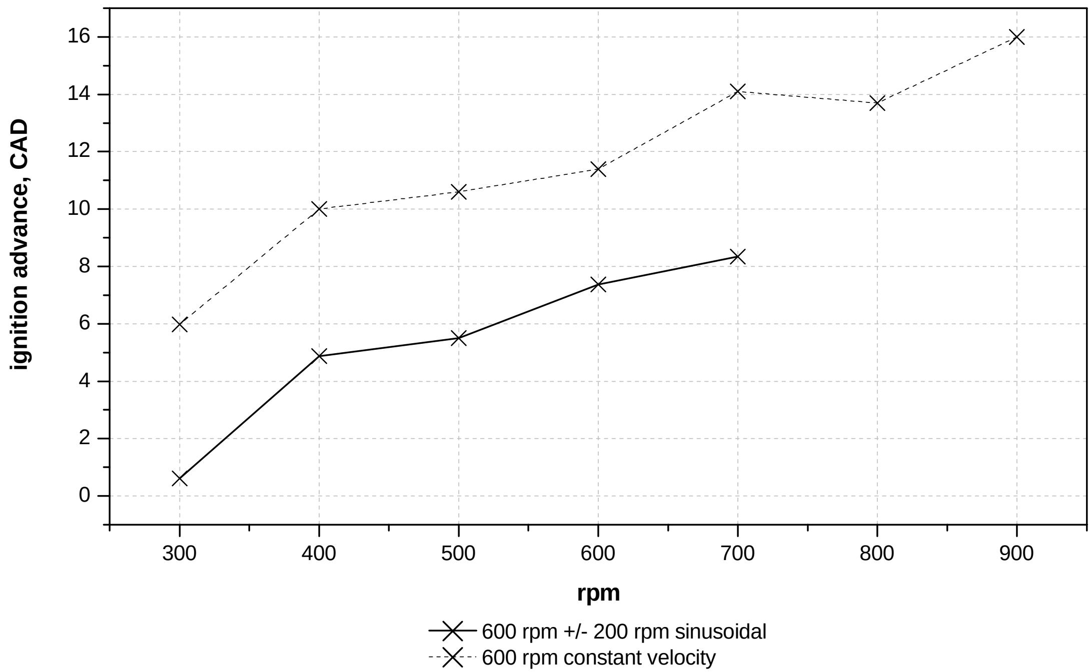


Motor current drift at varying operation temperature

Ignition Optimisation



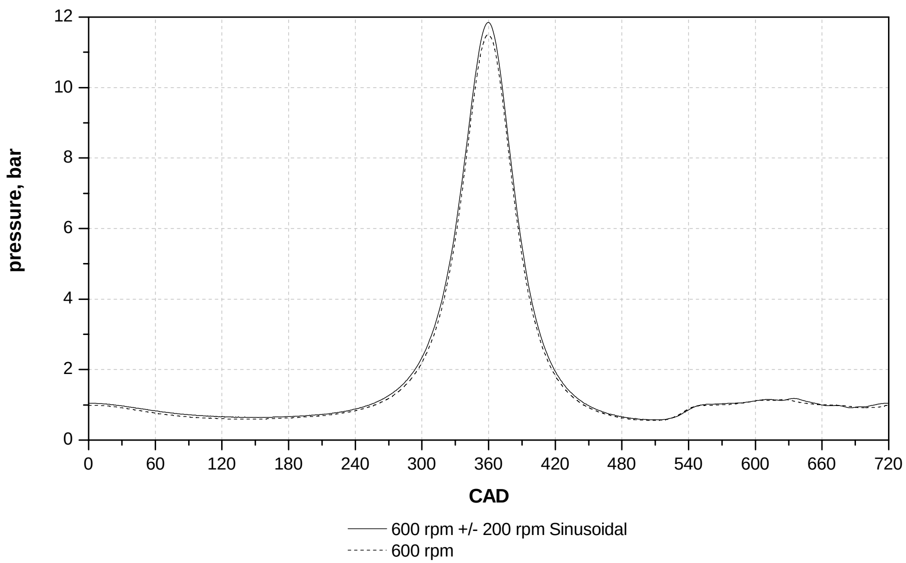
Spark ignition advance optimisation (constant speed)

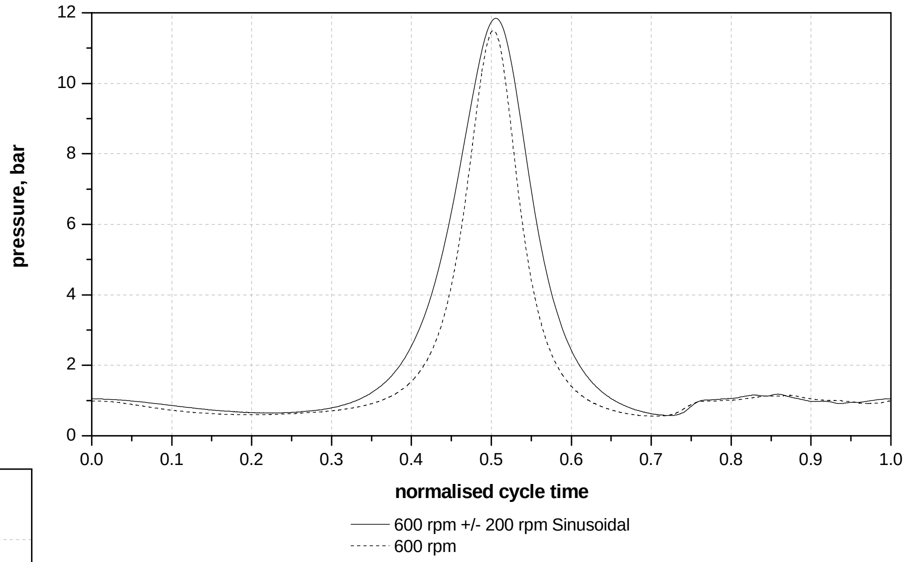


Optimised spark ignition advances at varying engine speed

RESULTS AND DISCUSSION - In-cylinder Pressure

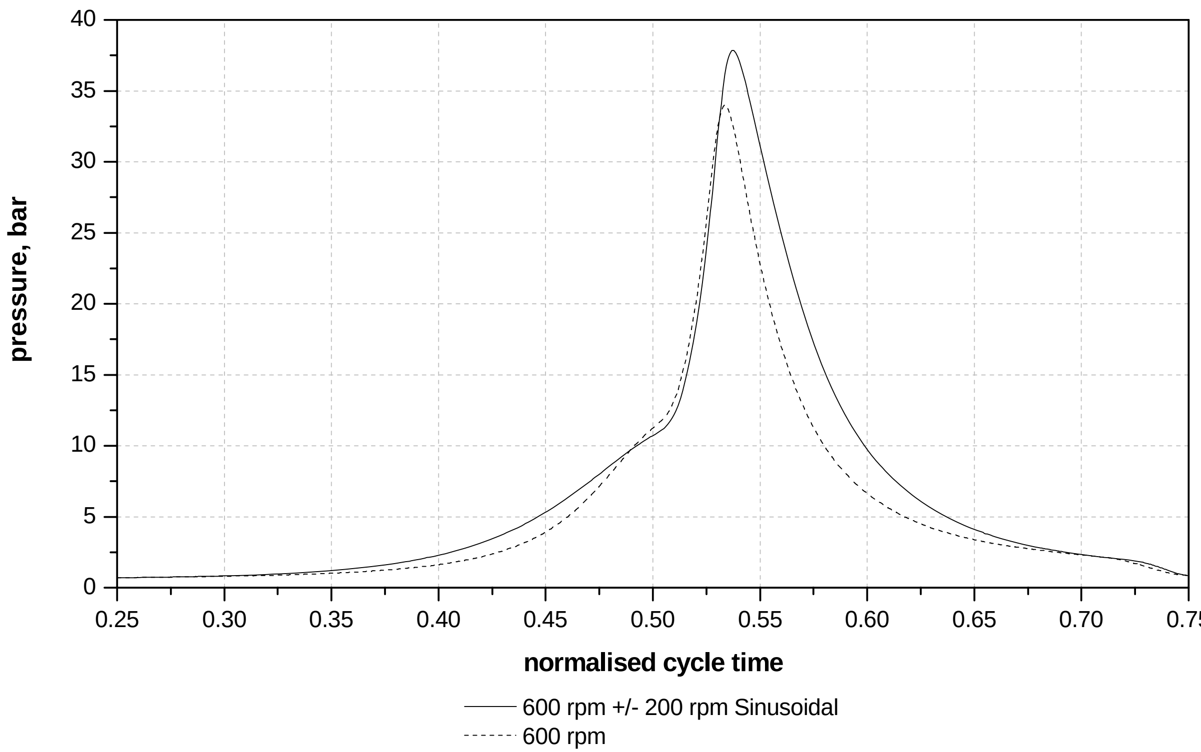
Motored cylinder pressure with conventional and QCV cycles vs. crank angle





Motored cylinder pressure with conventional and QCV cycles at normalized cycle time

- The QCV cycle uses a later optimized ignition timing, but produces a later but higher peak cylinder pressure, which further leads to an overall higher in-cylinder pressure during the expansion stroke.



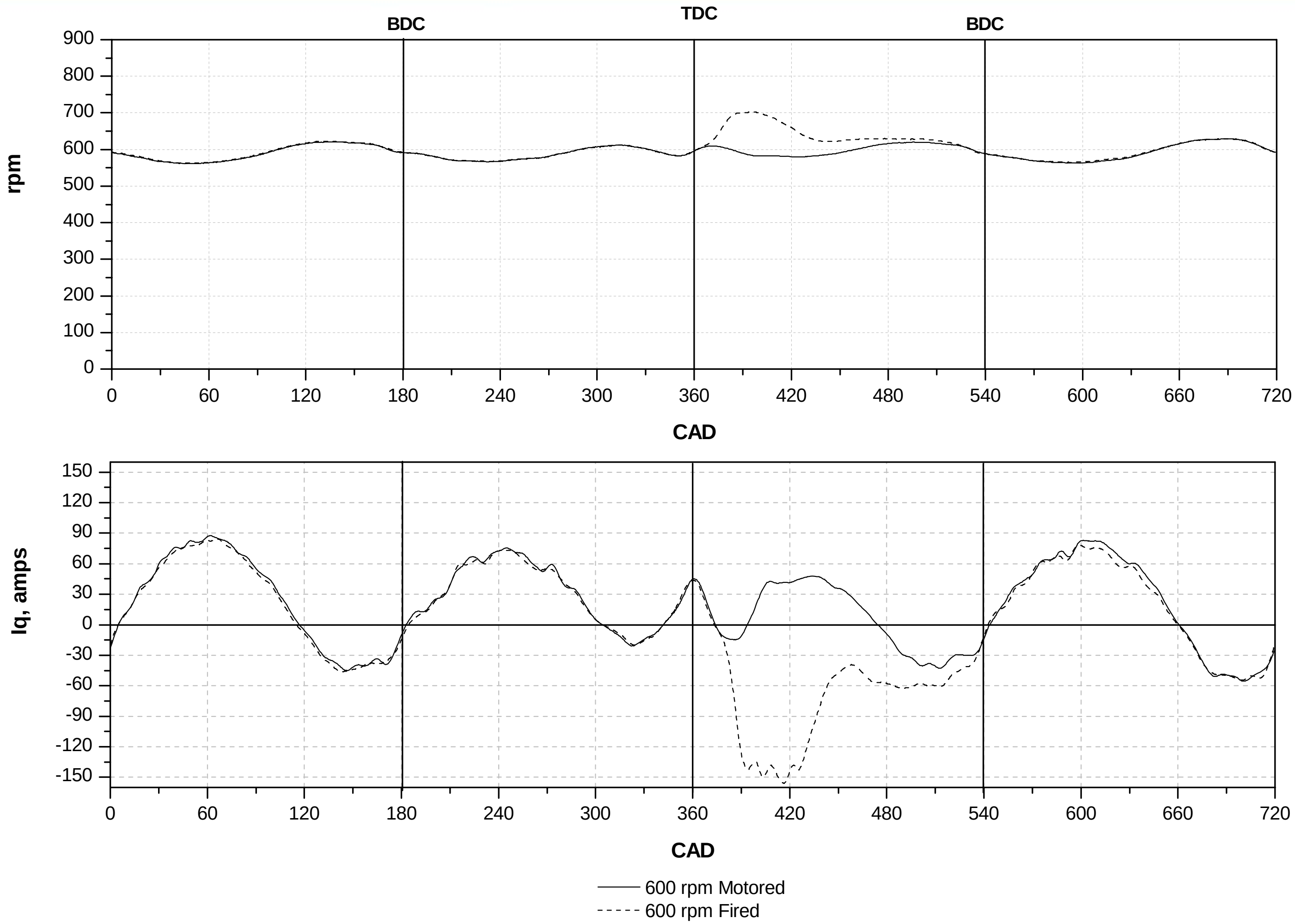
Fired cylinder pressure with conventional and QCV cycles

Evaluation of cycle pressure integral at each engine stroke (bar)

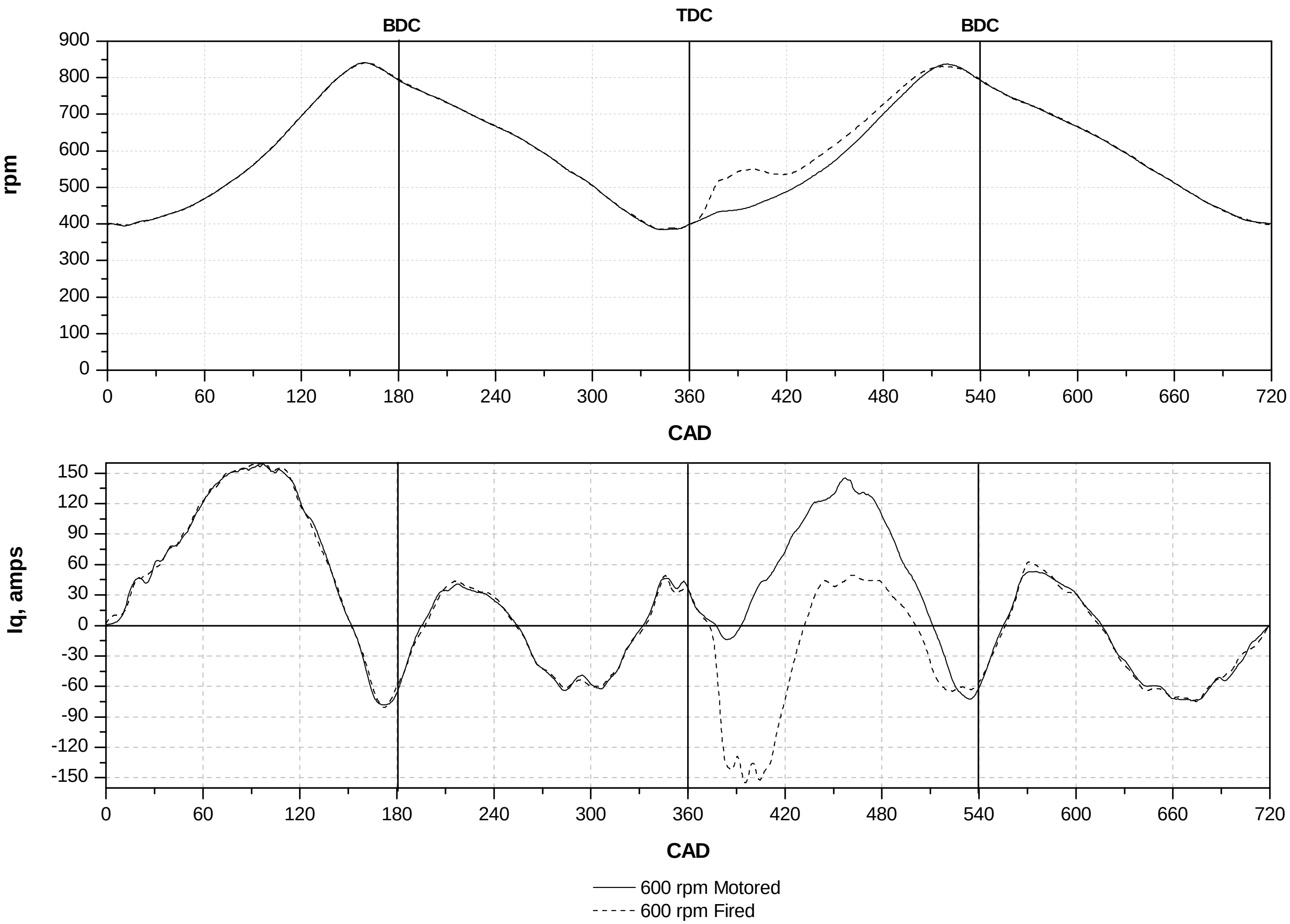
Stroke	**Motored**		**Fired**		**Change**	
	CSI	QCV	CSI	QCV	CSI	QCV
Intake	0.729	0.816	0.739	0.780	0.010	-0.036
Compression	2.754	3.616	2.966	3.627	0.212	0.011
Combustion	2.544	3.269	8.834	10.799	6.290	7.530
Exhaust	1.022	1.035	0.876	0.850	-0.146	-0.185
Cycle effective:	**1.761**	**2.183**	**3.253**	**3.840**	**1.492**	**1.657**

- The differences of the pressure integral among intake, compression and exhaust strokes between the fire and the motored cycles are minimal.
- Only the combustion stroke makes the contribution.
- Overall, the pressure integral of the QCV cycle is 11% higher than that of the conventional cycle.

Electric Current



Motored and fired crank speed and motor current of conventional cycle



Motored and fired crank speed and motor current of QCV cycle

Evaluation of cycle corrected current at each engine stroke (Amps)

Stroke	Motored		Fired		Change	
	CSI	QCV	CSI	QCV	CSI	QCV
Intake	21.48	75.90	20.48	76.25	-1.00	0.35
Compression	27.36	-6.35	27.94	-7.51	0.58	-1.16
Combustion	2.83	49.94	-67.91	-31.24	-70.74	-81.18
Exhaust	19.65	-22.79	18.25	-23.47	-1.40	-0.68
Cycle effective:	**17.90**	**24.10**	**0.99**	**4.52**	**-16.91**	**-19.58**

- The current integral of QCV is over 3 times higher than that of conventional cycle during the intake stroke.
- However, this loss has been largely compensated by the following compression stroke where the QCV cycle is actually producing current.
- Overall, if the difference between fired cycle and the motored one is assumed to be the contribution from combustion, it can be seen that the QCV combustion produces about 15.8% higher electric current integral than that by the conventional one.
- This agrees, in principle, with the improvement found from the pressure integral.

CONCLUSIONS

- The QCV concept proposed in this study can be hybridized with a sophisticated combined electric motor and generator unit to form a series-hybrid power-train to deliver the much desired high fuel efficiency and low pollutant emissions powertrain system with good power output.
- A proof-of-principle system has been developed. It consists of a high torque-to-inertia, high bandwidth, permanent magnet brushless ac electric machine, a single-cylinder research spark ignition (si) engine, and a control system.
- Two engine crank speed profile have been employed in the study, a constant 600rpm for a conventional cycle and a QCV cycle with a sinusoidal speed of 600rpm average with +/-200rpm amplitude. It found that with the conventional constant crank speed, the piston residual time at BDC is much longer than that at TDC. However, the chosen QCV cycle changes the piston movement profile and produces longer residual time at TDC to favour the combustion optimisation.

CONCLUSIONS

- With the QCV cycle, the piston movement is significantly slower than the conventional cycle during the intake stroke. This reduces the air flow velocity and therefore the throttling losses. The engine volumetric efficiency has been improved about 8% by using the QCV cycle.

- The work produced by a combustion engine is an integration of the pressure over an engine cycle. Clearly, the higher expansion pressure of the QCV cycle can produce higher work than it’s conventional counterpart. Overall, the pressure integral of the qcv cycle is 11% higher than that of the conventional cycle.

- The measure electric motor/generator current integral is another indicator of the system power output or requirement. The experimental results showed that the QCV combustion produces about 15.8% higher electric current integral than that by the conventional one.

engineexpo2009

Loughborough University

Thanks for Attention.

Question?