Electric Vehicle Motor and Power Management Control Preliminary Report

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The aim of this project is to develop a research test platform that integrates a high-power density supercapacitor with a lithium-ion battery modelled to a battery electric vehicles (BEVs) motor and power control management system. Developing energy management control between the supercapacitor and lithium-ion battery that satisfies the energy demands of the electrical motor and drive system to extend the life of a lithium-ion battery in a BEV. Initial scoping and three prototype phases comprising of theoretical, simulation, test and evaluation tasks resulted in an operational prototype requirement. The current phase of work is developing the operational prototype involving characterisation of the lithium-ion battery and supercapacitor into the research test model. Research is the final project phase, where an iterative process of test, evaluate, analyse and refine will be undertaken. To maximise the efficiency that can be attained from incorporating a supercapacitor into a BEV, to extend the life of a lithium-ion battery.

Contents

I. Introduction

The early electric vehicle (EV) appeared just after electromagnetism was discovered in 1820 with experimental electric cars. The invention of the rechargeable battery and more efficient and powerful motors provided a breakthrough around 1870. At the turn of the century 38 percent of automobiles were electric [9] and were driven by DC brushed motors controlled by contact controllers powered by lead acid batteries [10]. The current EV has many electric motor options, starting with the induction motor (IM) and switched reluctance motor (SRM) to the most common types being the permanent magnet synchronous motor (PMSM) and brushless DC motor (BLDCM). These are controlled by power electronics, DC to DC converters and DC to AC convertors, with electrical power provided by batteries and hybrid electrical power variations. [11] The current EV market is

[1] UNSW, School of Engineering & Information Technology. ZEIT450.

rapidly growing, in the month of March 2017, 93089 electric plug-in cars sold worldwide, compared to 59510 in March 2016 indicating a significant growth of 56 percent for the electric car market.[12]

The EV definition is diverse in functionality and configuration. For example, a solar challenge vehicle as shown in Figure 2 or Tesla-S electric car as shown in Figure 1 may come to mind. However, there is a myriad of EV types from an electric bus, train, formula E racing vehicle, aircraft, sports car, superbike, truck, van, motorbike, bicycle, mobility scooter, children's scooter, hoover board and many more types of EVs.

Figure 2 UNSW Solar Racing Team -SUNSWIFT [2]


Figure 1 Tesla[3]

The main market of EVs are cars and these vehicles are classified into certain types. The battery electric vehicles (BEV) has an electric motor drive which is powered by a large battery pack of 20-80kWh, it has no internal combustion engine (ICE), BEV's are charged by plugging into an electricity source for example a Tesla model S. Hybrid electric vehicles (HEV) have an ICE and electric drive motor where the batteries are charged by the engine. It has a medium size battery pack 6-12 kWh for example a Honda Civic Hybrid. Plug-in Hybrid vehicle (PHEV) which utilizes an ICE and electric motor to drive the vehicle. The batteries are able to be charged from an external electrical source. It is able to operate like a hybrid electric vehicle by using the electric and petrol motor to achieve greater fuel efficiency. It has a medium size battery pack of 6-12 kWh for example the Toyota Prius. Range extended electric vehicle (REEV) which are a small added feature to BEVs to enhance the range, for example the BMW i3 has a range extender option to the BEV version which is a small ICE (0.6l) with limited fuel (10 litres) to provide charge to the battery to extend the range. The various types and configurations are shown in *Figure 3*. The main focus for this project will be on the control management BEV vehicle type.

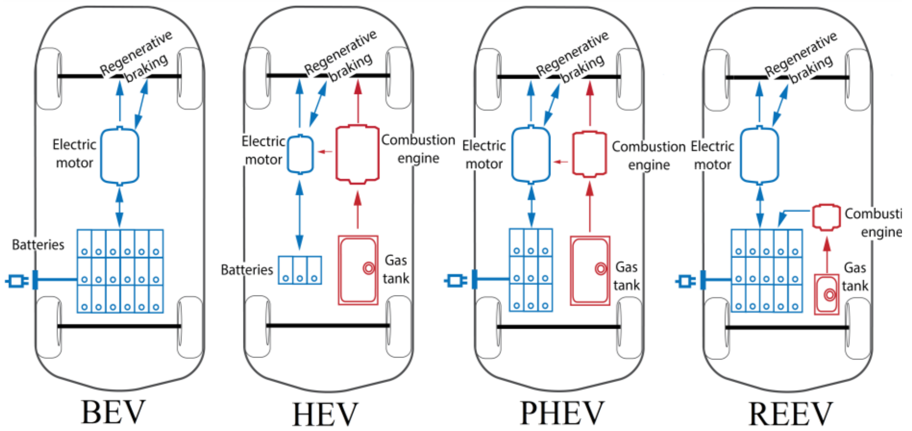

Figure 3 Electric vehicle types [4]

II. Project Scope

The BEV major groups of control management are defined as motor control, power control and auxiliary control. The project will focus on the control and management systems directly utilized to operate the drive portion of an electric vehicle. Therefore, auxiliary control will be defined as the all the other systems not directly related to a cars drive system, for example lighting, air conditioning, instrumentation etc. The control management will be divided into motor control and power control management. Once electrical motors, motor control and power management has been initially scoped and comprehended the project will progress to developing a test platform to then explore the prospects of efficiencies that can be attained for a BEV.

The project will focus on a PMSM or BLDC electric drive motor and associated motor controller, and lithium ion batteries as a basis to power the BEV. Physical and simulated models of motors, motor controllers and battery controllers will be utilised to develop a research test platform for conducting the research. The details of the project plan is detailed further in the project management section.

III. Aim

The aim of this project is to develop a research test platform that integrates a high-power density supercapacitor with a lithium-ion battery modelled to a battery electric vehicles (BEVs) motor and power control management system. Developing energy management control between the supercapacitor and lithium-ion battery that satisfies the energy demands of the electrical motor and drive system to extend the life of a lithium-ion battery in a BEV.

IV. Literature Review

The review will be in divided into three sections for this project. The electrical motor and control, battery control management and efficiencies associated with electrical motor control and power management control for BEVs. There is also be continuous review of research material during each of the project prototype phases.

A. Electrical motors and Motor control management

1. Electrical motors

There is a myriad of electrical motors used in EVs. The two categories of commutator and commutatorless machines. The commutator DC wound field and permanent magnet field machines are the earlier machines and have been superseded by the commutatorless machines. The commutatorless machines have four groups of IM, synchronous, doubly-salient and Vernier, each of these groups have different configurations associated with each groups. The synchronous machine(SM) group has the advantages of higher efficiency, power density and torque density over the IM and SRM.[11, 13]. The BLDC motor has the added advantage of low rotor generated heat over IM with the ability operate at unity power factor unlike the IM achieving 85%.[10] There are slight differences between the two SM where the PMSM has moderately higher efficiency and lower torque ripple than the BLDC, where the BLDC motor has moderately higher power density and higher torque density compared to the PMSM.[13] It is expected that both PMSM and BLDC motors will equally share the BEV market of electrical motor drives.

2. PMSM and BLDC motor

The PMSM and BLDC motor is a synchronous motor with permanent magnets on the rotor and windings on the stator as shown in *Figure 4*. Permanent magnets create the rotor flux and the stator windings create electromagnet poles which are electrically displaced 120° from each which are excited sequentially to create a rotating field, the rotor is attracted by the magnetomotive force of the stator.[7] The process of the rotor, attracting and repelling force from the electromagnet poles of the stator, is the fundamental mechanism used in synchronous permanent magnet motors. The angle between the rotors magnetic axis and the stators rotating magnetic field axis must be controlled to produce torque and the rotor position is required to maintain synchronization. The characteristic difference between the PMSM and BLDC motor is the shape of the driver voltage, which is a result the wiring distribution of the stator coils. This produces different back electromotive force (EMF) where the PMSM back EMF is sinusoidal and the BLDC motor back EMF is trapezoidal. [7, 8, 14]

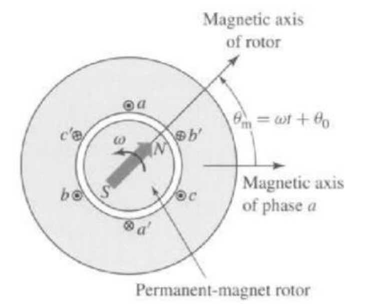

Figure 4 Permanent magnet synchronous motor [6]

3. Electrical motor control management

The PMSM requires a sinusoidal three-phase current driver signal and the BLDC motor requires a rectangular block shaped three-phase driver signals. Due to the difference in stator distributed winding design this enacts different control and management requirements detailed Table 1.The common BLDC motor controller structure [15] is shown in Figure 5 which is electronically commuted using a six step method that develops a three-phase rectangular voltage system to create a rotational field by the combinational logic.[14] A six step commutation signal is pulse-width-modulated to drive the three-phase inverter bridge configuration.[16]. The hall sensors provide speed feedback for speed control and positional feedback to generate precise firing commands to

BLDCM	PMSM
Input direct currents	Input sinusoidal current
Trapezoidal back EMF	Sinusoidal back EMF
Stator flux position commutation each are 60°	Continuous stator flux position variation
Only two stator phases energized at the same time	Possible that three phases are energized at the same time
Torque ripple at commutation	No torque ripple at commutation
Low order current harmonics in the audible range	Less harmonics due to sinusoidal excitation
Higher core losses due to due to harmonic content	Low core loss
Less switching losses	Higher switching losses at the same switching frequency
Control algorithm are relatively simple	Control algorithm are mathematically intensive

Table 1 PMSM and BLDC motor comparison [8]

the combinational for the three-phase inverter bridge. Current feedback provides torque control by adjusting the PWM duty cycle.

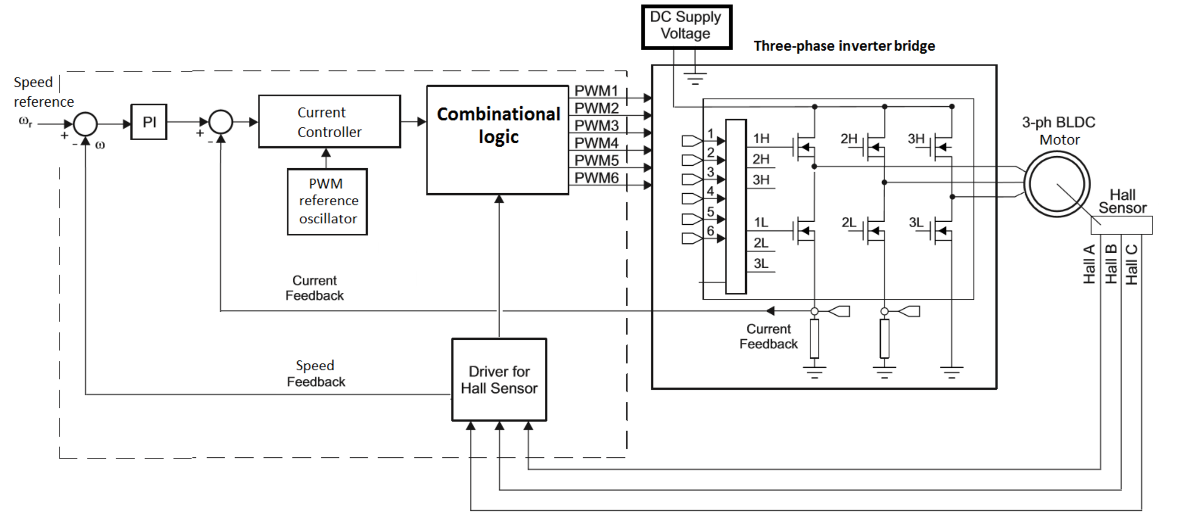

Figure 5 Structure of a BLDC controller

B. Power control management

1. Lithium ion battery

This project will focus on a similar battery type used in the Tesla S, 7104 18650 lithium-ion battery [17] cylindrical batteries make up the Tesla-S 82KWh battery pack. A cell 18 millimetres in diameter and 650 millimetres in length. The exact specifications of the Tesla battery are not known as this is a highly protected intellectual property characteristic to the company. For this project a Sony US18650VTC4, 3.7V 2000mAh 18650 battery will be used. The cell is a Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NMC) cathode with a graphite anode. The cells manufacturers performance specifications are shown in Figure 6, with a standard charging condition of constant current 2A and constant voltage 4.2V $\pm$0.005V. The battery has to be operated within the maximum 4.2V to minimum cutoff voltage of 2.5V and maximum discharge and charge current limits as specified, if operated outside of these limits damage may occur to the cell and this results can be catastrophic. Since battery cells are used in series and parallel combinations to form battery packs, a Battery Management System (BMS) is employed to monitor each cells voltage, the packs charge and discharge rates and State of Charge (SOC). The BMS will regulate the current as required ensuring it operates within the cells performance criteria and disconnects the battery from the system if the upper or lower thresholds are met to prevent damage to the battery.

Nominal Capacity (0.2C discharge)	2100mAh 7.77Wh	average capacity 3.70V (average discharge voltage)
Rated Capacity (0.2C discharge)	2000mAh 7.40Wh	minimum capacity
Capacity at 1C	2002mAh 7.30Wh	average capacity
Capacity at 10A	2035mAh 7.01Wh	average capacity
Nominal Voltage	3.7V	
Internal Impedance	12mΩ Typ.	measured by AC1kHz
Cycle Performance	60% Min. of Initial capacity at 500 cycles	10A discharge

Figure 6 Sony UUST18650VTC4 performance [1]

A lithium-ion battery has a limited number of cycles, the number of cycles will differ depending on how it is controlled within its performance thresholds. The life is dependent on the depth of discharge (DOD), rate of discharge, rate of charge and temperature. A partial discharge cycle, low discharge rate and low charge rate reduces the stress on the battery and prolongs its life.

2. BEV power system

A common structure of a power management system utilized in BEV is shown in *Figure 7*. DC/DC converters are often used to interface the battery bank to the inverter and motor. As the motor operates at a higher voltage than the battery installed. A common converter used in BEV is the universal DC/DC boost/buck converters. [18] Where power is able to flow from the battery to the DC bus and able to flow during regeneration from the DC bus to the battery. A power management system is used to control and monitor the BEV operation.

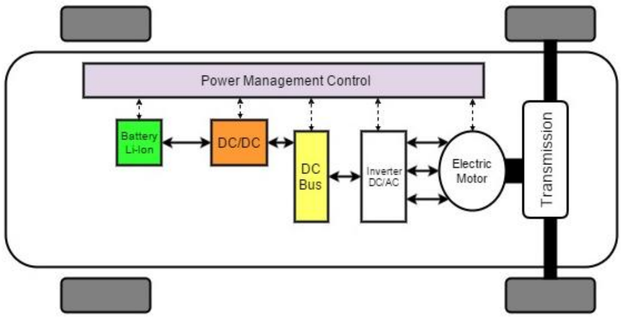

Figure 7 BEV power management system

3. Regenerative braking

Regenerative braking uses the electric motor as a generator to provide braking. Unlike conventual disc brakes where the energy in braking is lost as heat. Regenerative braking is able to recover the energy to the battery for storage.[19] The United States Advanced Battery Consortium and the Department of Energy (DOE) have provided goals for discharge/regen power and available energy in an HEV, and have developed hybrid pulse-power-characterization (HPPC) tests to determine if these goals are met.[20]

4. Supercapacitors

The supercapacitor is a type of electrochemical double layer capacitor (EDLC) that stores a charge electrostatically using reversible adsorption of ions of the electrolyte onto active materials that are electrochemically stable and have large accessible specific surface area. Charge separation occurs on polarization at the electrode–electrolyte interface, producing what Helmholtz described in 1853 as the double layer capacitance.[5]

The supercapacitors have a very high capacitance in the farads range compared to electrolytic of microfarads, though they operate at a low voltage typically 2.7V. [21] To operate at a higher voltage they are connected in series and require monitoring circuity for balancing and overvoltage protection. The advantages of supercapacitors is that it can be charged and discharged 100,000 times with minimal degradation of performance with a lifespan of 10 to 20 years. The low equivalent series resistance provide high power density and high load currents, but have low energy density. [22] The energy density and power density comparison of electrolytic capacitors, supercapacitors, lithium ion batteries with other power sources are shown in Figure 8.

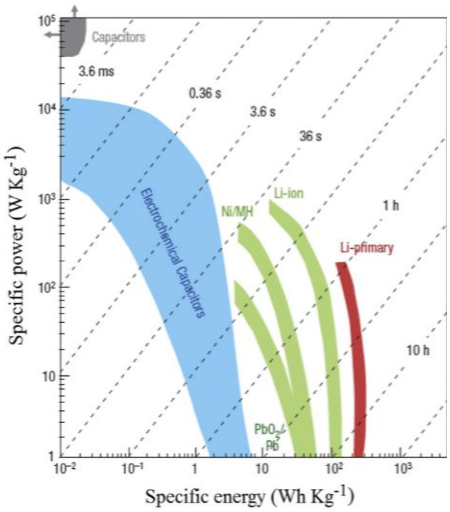

Figure 8 Ragone plot power verse energy densities [5]

V. Project Management

The project has several segments to aid in the projects development comprising of research, theory, simulation, physical test, measure and evaluation of a components to build a body of knowledge to ultimately progress to attaining an efficiency. The project plan is a hybrid evolutionary spiral model approach as shown in Figure 9, designed and selected to build a body of knowledge and result in a physical and/or simulation research test platform that will be used to attain an efficiency.

A. Schedule

The complete schedule is shown in appendix A the main topics and objectives of each phase are Initial Scoping and Prototype 1, carried out during Feb to Mar 17, initial scoping to research theory of operation of BLDC motor drive and control systems. Prototype 1 -Trial physical small motor drive system and larger motor drive system to assist in BLDC motor and controller education.

Prototype 2 - Mar - Apr 17 Determine a reference model, scale a design model and define the scope. Part A Create a simulation model. The simulation model has been deconstructed into smaller function to enable development easier and attainable. Part B As required for the simulation model test, measure and evaluate small and larger physical motor system.

Prototype 3 – Apr - May 17 – Simulate, Test and Evaluate to attain initial research test platform.

Operational Prototype Requirements, May 17 Design requirements of control research test platform. Project Preliminary Report and VIVA. Operational Prototype - May – Jul 17 Construct, test and evaluate control test platform. Conduct research - Jul – Oct 17 - Conduct research on test platform Test and Evaluate results of control improvement. Project Closure Sep - Oct 17 finalize documents and presentation.

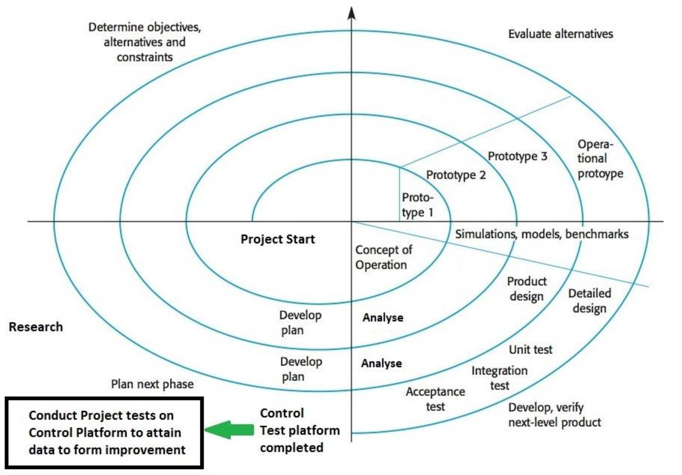

Figure 9 Test platform evolutionary schedule

VI. Work completed to date

The project management gave an overview of the project schedule and associated milestones to develop a physical and/or simulation research test platform. Each of the milestones are summarized in the following sections.

A. Initial scoping and Prototype 1 - Electrical motors and Motor control management

The initial scoping comprised of several sections on electrical motors and motor control management involving theoretical, simulation, test and evaluation tasks in order to gain an understanding of PMSM and BLDC motors and control management. The theory section clarified the theoretical principles and operation principles of a PMSM and BLDC motor. The simulation section enabled several components of BLDC motor control and interfacing to a physical BLDC motor. The test and evaluation section carried out testing and measurements of two BLDC controllers and motor systems. A small system comprising of a 15w motor and a large system comprising of a 3kW motor. This testing and measuring were to reinforce theoretical principles and to provide comparison to the theoretical signals and simulation results.

1. Electrical motor theory

The electric drive motor of choice for this project is the SM group of motors which is the PMSM or BLDC motor configuration. The original knowledge of electrical motors was limited to the basic principle of brushed DC motors. Therefore, a large knowledge gap existed and it was necessary to gain a solid understand of the electrical motor theory. The approach taken was to build up the knowledge from the beginning with Maxwells equations to magnetic circuits and magnetic material. Understanding magnetic circuits, flux linkage, inductance and energy. Applying the principles of electromechanics explaining magnetic fields, Faradays law and rule hand rule. [23] Applying these principles to the AC excitation waveforms of voltage and flux in AC power systems. Expanding to the electromechanical energy conversion principles. Lorentz force law simplified and expanding on the very useful right hand rule to the rotating machine basic concepts and the magnetomotive force of distributed windings. The distribution of windings is what distinguishes the PMSM and associated sinusoidal signal compared with the pulse or trapezoidal signal associated to a BLDC motor. This refining of the distribution of windings is to produce close approximation to a sinusoidal space distribution of the magnetomotive force for a PMSM. Building on the rotating magnetomotive force concept in AC machine single phase winding and expanding this to the rotating magnetomotive force in AC polyphase winding machines[7] as shown in Figure 10.

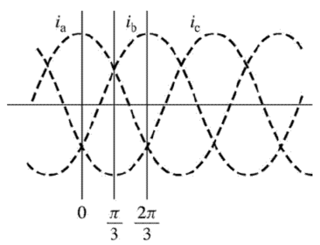

Figure 10 Instantaneous three-phase currents [7]

With the required drive signals for the AC polyphase machine or PMSM are shown in Figure 11. The detailed theory of the PMSM and BLDC motor are described in the Initial scope and prototype report.[24]

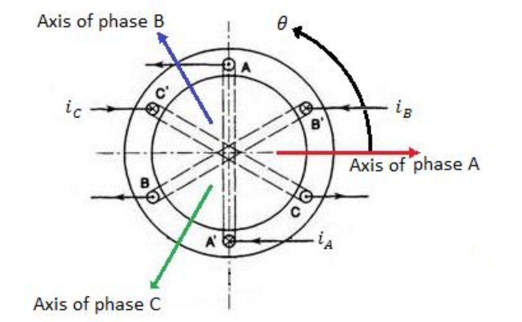

Figure 11 Two-pole three phase stator rotating magnetic field [7]

2. Simulation

Simulink and Matlab were used to construct components of BLDC motor control circuits. A combinational timing logic construed using a loop up table block provided the mechanism of receiving the hall sensors positional information of the motor position to enable the correct driver signals to an inverter bridge.

3. Test and measure a small BLDC motor and controller system

The concept was to reduce the risk and gain test data from a smaller manageable configuration. The motor used was a Maxon BLDC motor part number 335904, which comprises of Maxon motor EC16 part number 266519, a 16mm diameter brushless, 15 watt, 24 volt with three hall sensors. It has an encoder part number 201940, the encoder has 512 counts per turn, 3 channels and a line driver. The controller used was a Maxon Digital Controller 1-Q-EC Amplifier DEC 50/5, serial number 662039002322. The controller is a 1-quadrant amplifier for controlling electronically commuted (EC) motors with hall sensors to a maximum of 250 watts. This controller will interface with the motor sufficiently as the motor is only 15 watts maximum. The controller has digital speed control, open loop speed control or current control. These selections are selectable by the DIP switches. It has thermal protection against overload and input overvoltage protection.

This testing provided several learning outcomes. Confirming the trapezoidal control signals and corresponding hall sensor signals of the BLDC motor and controller. The measurement of the control and sensor signal were carried out using a Dranetz Power monitor PX5-400 serial number PX54FA01, data logger, and Tektronix TDS 1002B Digital Oscilloscpe serial number TDS1002B C105477. For an initial test of the small motor system it was very reliable, manageable and repeatable. A successful test and measure activity to develop and further investigate the intricacies of a BLDC motor and controller operation.

4. Test and measure a large BLDC motor and controller system

The aim to measure the control signals and operate a larger BLDC motor and controller system. A 3kW 72V BLDC motor and VEC220 Controller serial number VEC60048141121559. These were connected as specified by the user manual powered by power supply ADFA JS200189 0-200VDC 16A. During testing the motor would intermittently start and then only operate for a short period when accelerating. When the motor stopped it was unable to start again it was found that rotating the motor rotor a little would intermittently enable it to restart. It was also noted that when the motor accelerated the power supply voltage would drop. The power supply voltage was dropping below the low voltage threshold of 63V of the controller, this setting is required as to provide protection to the battery. The motor switching off during acceleration was associated with the power supply being unable to regulate effectively and therefore the controller would turn off as a safety precaution. It was determined from this fault to cease using this power supply and source another power supply with better regulation.

The replacement power supply was a Delta Electronika SM330-AR-22 which is able to provide variable 0-330V and 0-22A with a maximum power output limitation of 3300W. Two power supplies were connected in parallel to provide 72V, 40A enabling 2880W of power to the controller and BLDC motor. Since this is a no load test minimal current will be drawn from the power supplies. With the new power supplies the same fault occurred of intermittent operation. The motor halls sensors were tested and mapped to be operating correctly. The manufacturer was contacted and several tests were carried out on the motor and controller, including another controller used to operate the motor which lead to the controller being faulty. The controller was replaced by the manufacturer with a new one. The tests were repeated with successful results. The fault finding and testing of the motor and controller was a huge resource cost of time as it was a time consuming process. However the fault finding process did deepen my BLDC motor and controller understanding.

B. Prototype 2 phase

The aim of this section was to further define scope of research test model, carry out further research, theory of operation, simulation build up, construct some simple models, test and evaluate research test models. This was conducted in two parallel sections, test and evaluate various research models and research efficiencies of BLDC motors and controllers.

1. Test and evaluate various research models

Assessing various models that represents an EV control and motor drive system were required to incorporate regenerative braking. Further testing was carried out using the small Maxon BLDC motor and controller systems that was used in the initial scoping. The Maxon Digital Controller 1-Q-EC Amplifier does not have regenerative braking feedback to the power supply so this controller can not be utilized. However one option was to replace the controller with a dSpace interface operated by Matlab, Simulink and dSpace controls. A motor control interface containing a Smart Power Module chip FSB50450S is used to drive the motor. The logic and control functions would be carried out by Matlab, Simulink and dSpace. The power supply would be replaced by a lithium battery to replicated a BEV system. An initial efficiency consideration was for the enhancement of incorporating a supercapacitor. This adds to the complexity of the power management controller.

A simulation model using Matlab, Simulink and Simspace was discovered on the Mathworks examples library [25] could be modified for the research model used a PMSM drive, three-phase inverter, and PMSM controller connected to a battery. A lithium ion battery model could be utilized for the research model.

A complete HEV simulation model was also in the Mathworks examples library [26] the HEV model uses Simscape Electronics, Driveline, and Power Systems. There are two configurations one for system-level testing and one for power quality analyses. The electrical, battery, and vehicle dynamics systems can be tailored with various subsystems. The HEV model would have to modified to be BEV model and there were many feature and functions available using this model.

2. Efficiencies researched on PMSM and BLDC motor control

A comprehensive understanding of BLDC motor and controllers was forming, where sinusoidal control signals are required for a PMSM and rectangular or trapezoidal control signals are required for a BLDC motors and this is due to the motors stator winding design, therefore matching the control signals to the motor design. An initial pursuance was thought that an efficiency could be attained in the motor and controller relationship. This lead to further research of BLDC motors and controllers.

Numerous academic papers have been published on the efficiencies that have a researched related to PMSM and BLDC motors and control techniques applied. The simulation of speed control for a BLDC motor using a fuzzy logic controller incorporated into control structure which has simplicity of control with the required speed control and shorter response time providing more efficient speed control compared to a conventional BLDC controller.[27] Also a fuzzy logic controller incorporated in a conventional PI control that provided better dynamic response. [28-30]The efficiency improvement by simulating the elimination of torque dips due to the back EMF and instantaneous commutation currents by using small surface mounted magnets to overcome the non-ideal attribute of the BLDC motor to become a high performance drive.[31]

The BLDC motor control improvement to current control structures due to the limitations of measurement, variations in temperature, and the different rotor positions in the real control, the variance in electrical parameters of resistance and inductance from nominal values, increase the difficulty in current controller design by incorporating switching-gain adaptation control and model reference adaptive control resulted in reducing the current chattering to guarantee the steady-state accuracy but also improved the tracking speed to achieve a good transient performance.[32]

3. Prototype 2 analysis

The sinusoidal developed control signal for a PMSM and rectangular control signal for a BLDC motor are matched to the motors stator winding design. There are minor imperfections of each design detailed in *Table 1* and these have been previously researched and efficiencies developed. The design and development of PMSM and BLDC motors are highly engineered and have been refined over many years. Due to these factors to attain an efficiency, the research platform would need to incorporate a motor design and matching controller, this was deemed significant and there are no motor manufacturing and testing equipment readily available. Therefore decided for the next prototype phase is to focus on research and testing of models in relation to power control management.

C. Prototype 3 phase

The aim of this phase is to check and redefine scope of research test model if required, refine and incorporate improvements into research test model operation, simulation build up, construct model, test and evaluate test model. The scope is focusing on the power management and control aspects for the research model. The two sections in this prototype 3 phase is test and evaluative power management models and carry out research on BEV power management efficiencies.

1. Testing and evaluation of power management models

It was decided to start with the lowest portion of the power management structure starting with a lithium ion battery model. A Simscape Lithium Battery Cell Model – One RC branch equivalent circuit [33] was available.

The model equations and validation are defined in an IEEE conference paper "High Fidelity Electrical Model with Thermal Dependence for Characterization and Simulation of High Power Lithium Battery Cells,".[34] A simple thermal model is used to model battery temperature and the battery pack of the research test platform can be modelled by connecting multiple copies of the battery cell block. During this research phase the incorporation of using a supercapacitor and lithium ion battery to provide the electrical power for a BEV was determined as the efficiency to research. A Supercapacitor model example showing the charging and discharging characteristics as shown in Figure 12, where the supercapacitor is able to provide the initial instantaneous power to the load and able to absorb the power when decreasing in current is not meet by the battery and the supercapacitor absorbs the power preventing waste. A BEV has similarity when providing the initial power to the motor on initial acceleration and the characteristic of absorbing the power during regenerative braking and deacceleration. Therefore, incorporating this component into the research test platform as an efficiency improvement is plausible.

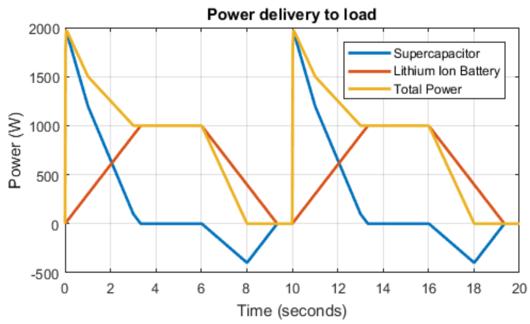

Figure 12 Power sharing of supercapacitor and lithium ion battery

2. Efficiencies researched power management in BEVs

The BEV suffer of the reliance purely on battery power that is once it disconnects from the electrical charge cycle that the power stored in the battery is what is available to use. The utilisation of that power for maximum transfer to mechanical energy through the motor and wheels is essential.

This research phase aims to research the possible efficiency's available for a BEV related to power management. There are suggestions of using dual mode hybrids operating in series or parallel modes with dual inverters enabled by DC to DC boost/buck converters. [18]

Three types of lithium-ion batteries ($LiFePO_4$, $LiMn_2O_4$ and NMC) and supercapacitors were modelled each power source the lithium-ion batteries are meet able to meet the DOE the HPPC requirements. The supercapacitor alone is unable due to its low power density. However a hybrid supercapacitor which has energy densities of 13Wh/kg, higher than a traditional supercapacitor had promise of meeting the demands of an EV.[20]

Multiple power sources of Fuel Cell banks, battery packs, and supercapacitors form a HEV. This multiple power source requires DC to DC converters and efficient power electronic conversion. Various converter topologies were compered from Boost converters, Multi-Device Boost Converter, Two Phase-Interleaved Boost Converter, Multi-Device Interleaved Boost Converter and the most efficient Four-phase interleaved DC to DC boost converter.[35] and an addition to this converter that has a sliding mode control design for an efficiency. [36]

A dual power source input using a fuel cell and battery analysed the interleaved boost converter DSP-based digital control highlighted an efficiency that extends the lifetime of a battery system. [37]

Bidirectional DC to DC converter would be a desirable application in this project a conventional full-bridge bidirectional DC to DC converter to compared to the proposed bidirectional isolated DC to DC design which was performed at a higher efficiency. [38]

A HEV research project integrating lead acid batteries, supercapacitors and ICE generator with power flow management algorithm enabling all three power sources to power a four wheel driven EV. The design did not meet the EVs load demands however it did improve dynamic performance.[39]

D. Prototype 3 analysis

The prototype 3 phase has refined the scope of the research test model during the simulation test and evaluation. No particular paper researched provided all of the aims required in this project, however each of research papers provides technical material and recorded performance data evidence that overlaps into the main objectives that are developing for this project. These will feed into the basis and scope of the project operational prototype requirements.

E. Operational prototype requirement

An EV research test model incorporating power management control of a lithium ion battery and performance enhanced by supercapacitors to provide an efficiency to a standard lithium ion powered EV as shown in Figure 13.

F. Operational Prototype

Initial characterisation testing of the supercapacitor is shown in Figure 14 with further work required on the current measurements to enable accurate data for the simulation model and research test platform.

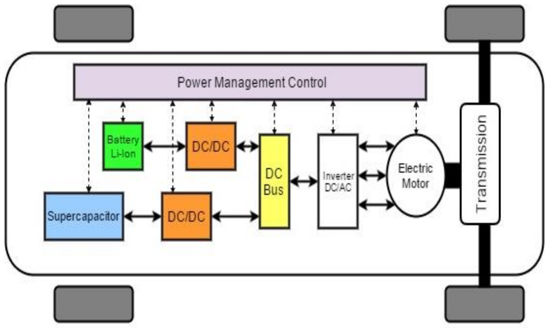

Figure 14 Operational prototype requirement structure

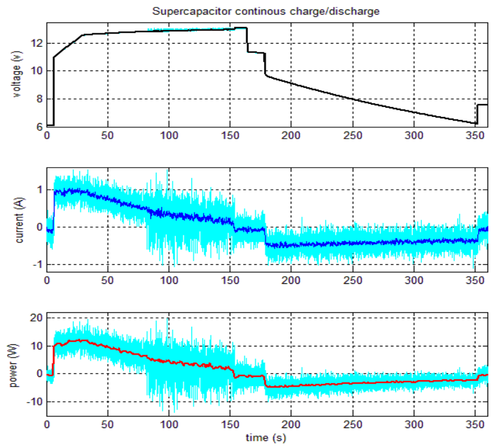

Figure 13 Initial supercapacitor characterisation

VII. Future Work

The schedule defined in appendix A show the future work tasks and milestones. The two major tasks planed for future work are Operational prototype and Research. The research test model will be simulated in Simulink and Simscape developed for testing and measuring the real power source components. A physical model is also being constructed however this has been identified as a high risk task. This is due to the lead time in parts and confirm time resources. This has already been experienced during the physical testing sections. The achievement of a physical research test model is therefore a desirable deliverable.

A. Operational Prototype

Confirm research model is representative of real model. Defining the load characteristics to be applied to the research test model are relative to acceleration and deacceleration correlate to acceleration power and regeneration power.

Baseline research model configuration. Testing and data logging of each of the power components. Designing and constructing a simulation model that reflective representation of the real power device.

Baseline performance characteristics. Construct the complete research test platform with lithium ion batteries. Carry out baseline test the battery as an EV to form the baseline of the lithium battery only powered system.

B. Research

Incorporate research improvements into research test model. Entails the incorporation of the power management system and interfacing the supercapacitor into the research test model.

Simulation build up. Designing and constructing a simulation model with the power management controlling the lithium ion battery and supercapacitor.

Construct model. In parallel tasking of the simulation model the construction of the physical model will be carried out. There will be gaps in construction due to parts however this will allow time for work to be carried out on the simulation task.

Test and evaluate improvements of research test model. This will be an iterative process of test, evaluate, analyse and refine. The aim is to maximise the efficiency that can be attained from incorporating a supercapacitor into this research test model.

VIII. Conclusion

A clear project plan has been established and is progressing in a clear direction. Significant research and thorough analysis of each prototype phase has established the operational prototype requirement. Currently progressing into the operational prototype phase, characterising and constructing the research test model.

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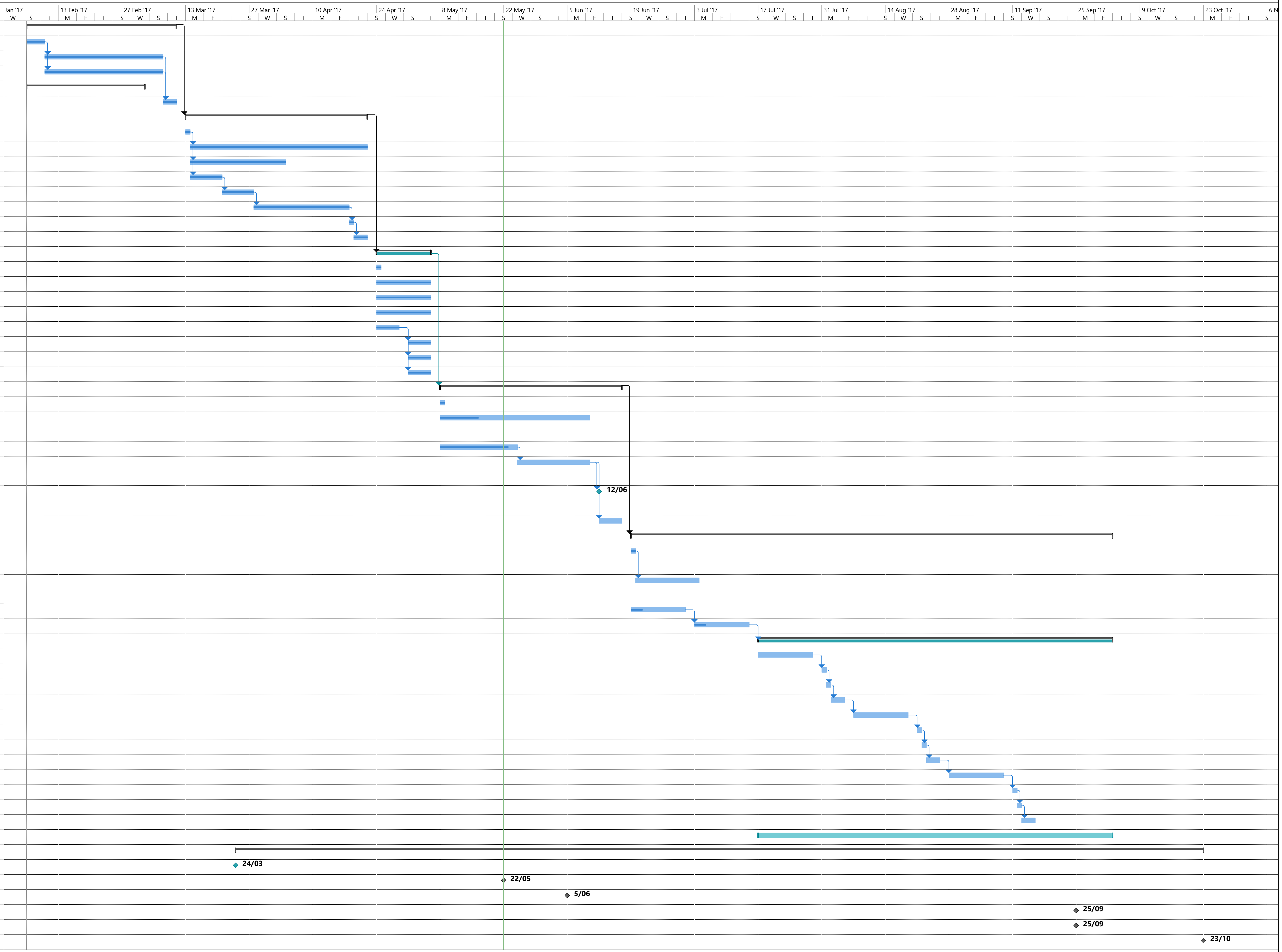
Appendices (Separate Document)

Appendix A – Project schedule

Electric Vehicle Motor and Power Management Project Schedule

Appendix A

ID	Task Name
1	**Initial scoping and prototype 1**
2	Research
3	Theory of operation
4	Simulation
5	**Test Physical system**
8	Document and report
9	**Prototype 2**
10	Define scope of research test model
11	Research
12	Theory of operation
13	Simulation build up
14	Construct model
15	Test and evaluate test model
16	Analyse
17	Document and report
18	**Prototype 3**
19	Define scope of research test model
20	Research
21	Theory of operation
22	Simulation build up
23	Construct model
24	Test and evaluate test model
25	Analyse
26	Document and report
27	**Operational prototype**
28	Finalsie research scope
29	Confirm research model is representative of real components
30	Baseline research model
31	Baseline research model configuration
32	Research test platform baseline complete
33	Document and report
34	**Research**
35	Research scope defined and accepted
36	Incorporate improvements into research test model
37	Simulation build up
38	Construct model
39	**Test, Evaluate, Analyse and Refine**
40	Test
41	Evaluate
42	Analyse
43	Refine
44	Test
45	Evaluate
46	Analyse
47	Refine
48	Test
49	Evaluate
50	Analyse
51	Refine
52	Document and report
53	**Project Document Milestones**
54	MOU signed
55	Preliminary report
56	Viva presenataion
57	Project Seminar Report
58	Project Research Summary
59	Projectspecific deliverable



Project: Sch	Task	Milestone	Project Summary	Inactive Milestone	Manual Task	Manual Summary Rollup	Start-only	External Tasks	Deadline	Manual Progress
Date: Mon 22/05/17	Split	Summary	Inactive Task	Inactive Summary	Duration-only	Manual Summary	Finish-only	External Milestone	Progress	