AN OMNI-DIRECTIONAL DESIGN TOOL FOR SERIES HYBRID ELECTRIC VEHICLE DESIGN

A Thesis

by

NEERAJ SHRIPAD SHIDORE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Electrical Engineering

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Approved as to style and content by:

Mehrdad Ehsani (Chair of Committee)	Karen Butler-Purry (Member)
Shankar Bhattacharyya (Member)	Reza Langari (Member)
Chanan Singh (Head of Department)	

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ABSTRACT

An Omni-Directional Design Tool for Series Hybrid Electric Vehicle Design.

(December 2003)

Neeraj Shripad Shidore, B.Eng., Government College of Engineering, Pune, India

Chair of Advisory Committee: Dr. Mehrdad Ehsani

System level parametric design of hybrid electric vehicles involves estimation of the power ratings as well as the values of certain parameters of the components, given the values of the performance parameters. The design is based on certain mathematical equations or ‘design rules’, which relate the component parameters and the performance parameters. The flow of the design algorithm is uni-directional and fixed, and cannot be altered.

This thesis proposes a new method for such parametric design, called omni-directional design, which does not have a fixed sequence like the conventional design, but can start with any parameters of the designer’s choice. The designer is also able to specify the input parameters over a range, instead of a point (one, fixed value) input. Scenarios having a point input, but values of an output which can vary over a range for the point input, can also be studied.

To my parents…………

ACKNOWLEDGEMENTS

I would like to express special gratitude to my parents for their constant encouragement and support throughout. It is because of the discipline and virtues that they instilled in me that this work has been possible. I seek their blessings. I also thank my sister, Teja. She has been a source of constant love and affection since my childhood.

I would like to express my gratitude to Dr. Ehsani for his stimulating guidance, constant encouragement and suggestions throughout the process of the work. The two years of working with him have given me much insight into many aspects in the field of hybrid vehicles and motor drives, far beyond the scope of my thesis work. I also take this opportunity to thank my committee members Dr. Bhattacharyya, Dr. K. L. Butler –Purry and Dr. Langari for taking interest in my thesis work and providing me with invaluable suggestions. Special thanks to Dr. Gao for his constant help throughout the process of this thesis. The cooperation from all the lab members of the Motor Drives and Advanced Vehicle System Research Program is gratefully acknowledged.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
DEDICATION		iv
ACKNOWLEDGEMENTS		v
TABLE OF CONTENTS		vi
LIST OF TABLES		viii
LIST OF FIGURES		ix
CHAPTER		
I	INTRODUCTION	1
	A. Introduction	1
	B. EV and HEV history	3
	C. Hybird vehicle architectures	4
	D. Omni directional tool concept	9
	E. Research objectives and thesis overview	10
II	SERIES HYBRID ELECTRIC VEHICLES(S-HEV)	12
	A. Introduction	12
	B. Series hybrid drive train	12
	C. Control strategy	16
	D. Equations related to major components	20
	E. Summary	32
III	CONVENTIONAL DESIGN OF A SERIES HYBRID ELECTRIC VEHICLE	33
	A. Introduction	33
	B. Design example	33
	C. Summary	42
IV	CONCEPT OF OMNI-DIRECTIONAL DESIGN TOOL	43

CHAPTER Page

A. Introduction 43
B. The new approach 43
C. Exploiting the new approach 52
D. Realization of the new approach 59
E. Limitations of the new tool 66
F. Summary 67

V OMNI-DIRECTIONAL DESIGN TOOL 66

A. Introduction 68
B. The user interface 68
C. Design examples 77
D. Summary 96

VI SUMMARY AND FUTURE WORK 97

A. Summary 97
B. Future work 98

REFERENCES 99

VITA 101

LIST OF TABLES

Page

Table 1: Average power with full and no regenerative braking for different drive cycles………………………………………………………………..………… 39

Table 2: Freedoms of the new design tool and possible applications……………..… 60

Table 3: Results after 2nd iteration for point input- range output scenarios………… 91

Table 4: Results after 3rd iteration for point input- range output scenarios………… 93

LIST OF FIGURES

FIGURE		Page
1	Typical series and parallel hybrid vehicle architectures	5
2	Parallel hybrids	7
3	Series hybrid electric drive train	14
4	Engine characteristics and optimal operating region	15
5	Series hybrid electric power train with various controllers	17
6	Maximum SOC control strategy	19
7	Engine turn on and turn off control	20
8	Speed torque characteristics of a traction motor	21
9	Speed torque characteristics of a 60HP motor for x=2,4 and 6	22
10	Average and instantaneous tractive power versus time	25
11	Instantaneous power and average power with full and zero regenerative braking in some typical driving cycles	27
12	Variation in PPS energy over a drive cycle	28
13	Variation in charging and discharging efficiencies with state of charge	29
14	Torque at the wheels and the tractive effort (Ft)	30
15	Tractive effort versus speed for a traction motor of x=6	31
16	Speed torque and speed power curve for the designed traction motor	36
17	Acceleration performance	37
18	Traction effort and resistance of vehicle versus vehicle speed	38

FIGURE Page

19 Simulation results for the given engine and the PPS rating 40

20 Operating point of the internal combustion engine 41

21 Variables of a series hybrid considered for design....................................... 44

22 Flow of the design procedure in a conventional design process 45

23 A DC voltage source with a variable resistive load 46

24 Single dimensional plots of V and R as well as the output I 48

25 Example of a point input - finite range output scenario 49

26 Flow of design according to the new design method 51

27 Starting the design with the traction motor 53

28 Starting from some variables in some components...................................... 54

29 Boxes for the set of equations considered 66

30 Screen shot of the first page 69

31 Block diagram indicating the components available for design.................... 70

32 The design input GUI 72

33 Design GUI with values entered for some inputs... 75

34 A completed design 76

35 Input variables for the point input – point output scenario 79

36 a)Drive cycle b)motor power versus time c) engine power versus time d) battery power versus time e) battery energy level versus time.................... 80

37 Two dimensional plots for the first iteration 83

38 Two dimensional plots for the final iteration 85

FIGURE Page

39 One dimensional plots for range input range output scenario 86

40 Three dimensional plot of the range input range output scenario 87

41 Iteration 2 inputs-outputs for the point input range output scenario 90

42 The one dimensional plots for the first two iterations 92

43 One dimensional plots for the first three iterations (point in range out) 95

CHAPTER I

INTRODUCTION

A. Introduction

Transportation is a major source of energy consumption and airborne pollutants around the world. The energy consumed by millions of vehicles on the highways accounts for the majority of petroleum usage around the globe and in this process billions of tons of airborne pollutants are introduced in the atmosphere each year. In response to concerns over environmental degradation, the California Air Regulatory Board (CARB) proposed regulations, which would require a progressively increasing number of automobiles to be zero emission automobiles, beginning the year 1998. Following California's lead, several other states representing nearly 40% of the vehicles on the road have also adopted or are seriously considering similar regulations [1]. Presently, only electric, low emission Hybrid vehicles and fuel cell powered vehicles can meet the goals outlined in the CARB regulations using existing technologies.

1.Electric vehicles

Electric vehicles are a promising technology for the long-range goal of energy efficiency and reduced atmospheric emissions. A well-designed electric motor drive can yield close to 90% efficiency and since the onboard systems in an electric vehicle are powered by batteries and electric motors, there are no toxic emissions. Some argue that the use of electric vehicles neither improves efficiency nor reduces toxic emissions. It merely shifts the energy production and pollution away from the urban centers to the areas where

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electricity is produced. The increased size and resulting efficiency gains of electric generation facilities and the high efficiency of the distribution systems results in better use of natural resources when compared to conventional vehicles. According to several reports, widespread use of electric vehicles would reduce pollution not only in urban areas, but also across the rest of the country since electric utilities burn fossil fuels much more cleanly and efficiently [2]. Electric power plants can also be easily monitored for emissions since they are large stationary installations whose location is known where as an automobile's emissions can only be monitored at production and intermittent state inspections. Also, since a growing proportion of electricity is being produced by non-polluting sources like hydro electric, nuclear, solar and wind power, the pollution associated with electric power is decreasing. Despite the many beneficial aspects of the electric vehicle, many technical and social obstacles stand in the way. The most debilitating aspects of the electric vehicle are its limited range and lack of supporting infrastructure [3]. Using present technologies. Electric vehicles can achieve ranges of only 200-250 km before the battery is depleted. While this is sufficient for everyday use, it precludes the use of electric vehicle for long distance trips. Until an electric storage device is developed that can provide adequate range and quick recharging capabilities, the electric vehicle will have a limited role as a delivery vehicle or as a commute.

2.Hybrid vehicles

Hybrid vehicles offer higher efficiency and reduce emissions when compared with conventional automobiles, but they can also be designed to overcome the range limitations inherent in an electric vehicle. Hybrid vehicles utilize two distinct energy sources, usually an electric motor and an Internal Combustion Engine (ICE) to power the vehicle systems. The electric motor is used to improve the energy efficiency and vehicular emissions while the ICE provides extended range capability. Although the widespread use of electric vehicles would require a substantial investment in new infrastructure, current facilities can accommodate hybrid vehicles since the ICE runs on gasoline, diesel, or Compressed Natural Gas (CNG), which can be replenished quickly and are widely available [3]. The batteries used to power the electric motor can be either charged by the ICE or the electric machine, during regenerative braking. Hybrid vehicles provide an alternative to present automotive designs while research to develop advanced energy storage continues.

B. EV and HEV history

In the early years of automotive development, Electric Vehicles competed with the ICE vehicles for market share. The advantage of the electric vehicle was that it was quiet, clean, relatively powerful, and did not require a crank to start. Although the range of the electric vehicle was limited, long distance travel was not a major consideration since most autos were owned by the wealthy and were used within the confines of the city. ICE based designs lost out to electrics until the addition of the starter motor allowed the car to be started without a crank. From this point onward, the ICE gained prominence and has become the primary automotive propulsion technology.

The concept of a hybrid vehicle, one which operates from two distinct energy sources, was developed in the early twentieth century with a patent being issued to H.

Pieper in 1905. In these early hybrids, the electric motor augmented the power of the relatively weak ICE during acceleration. However, before these hybrids went into commercial production, ICE technology had progressed to the point that the assistance of the electric motor was no longer needed. Development of hybrid vehicles remained at a virtual standstill until the later 60s and 70s, when environmental concerns and increasing dependence of the U.S.A on foreign oil stimulated renewed research in this country. Since then, substantial progress has been made in the technology, and commercial production of hybrids has been on by automobile giants like Toyota, Honda and General Motors etc.

C. Hybrid vehicle architectures

A Hybrid Vehicle, as defined by Technical Committee 69 (Electric Road Vehicles) of International Electro Technical Commission, is one in which propulsion energy during specified operational missions is available from two or more kinds or types of energy stores, sources or converters with at least one store or converter onboard [3]. This definition is purposefully vague as energy sources also include fuel cells etc. Similarly, ultra capacitors and flywheels are examples of power sources. A more specific definition of a hybrid electric vehicle is given as a hybrid vehicle in which at least one of the energy stores, sources or converters can deliver electric energy.

Though many different configurations of power sources and converters are possible in a hybrid electric power plant, there are two generally accepted classifications, series and parallel.

In a series hybrid, only one energy converter provides torque to the wheels while the other is used to recharge an energy accumulator, usually a battery pack. The series configuration shown in figure 1 represents a typical design where the ICE/generator pair charges the batteries and only the motor actually provides propulsion. A disadvantage of the series hybrid arrangement is that three distinct energy converters are required, increasing the vehicle weight. The parallel configuration illustrated in figure 1 also represents a typical design, where both the ICE and the electric motor can provide torque to drive the wheels.

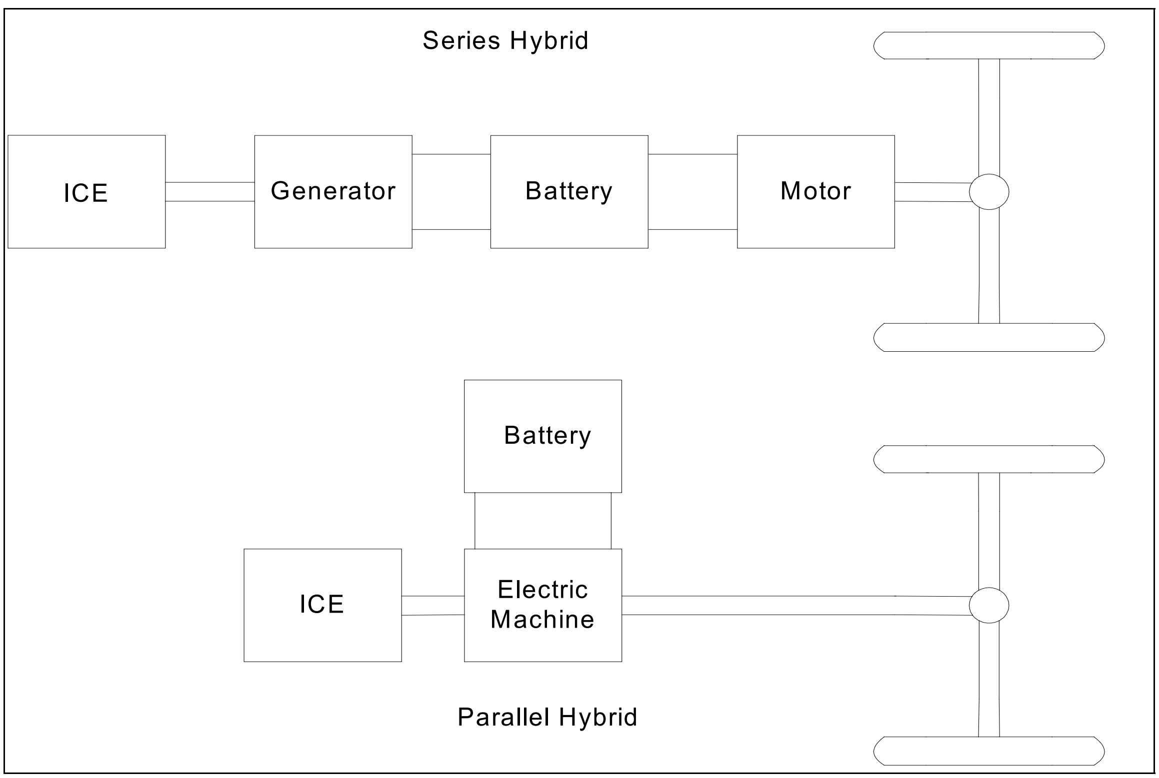


Fig. 1. Typical series and parallel hybrid vehicle architectures.

1.Series hybrids

Although the sizes and types of components used in a series hybrid drive train vary, their functional roles remain pretty much the same. An onboard generator maintains the state of charge of an energy accumulator and the energy from this accumulator is transformed by an energy converter into torque to drive the wheels. The main design parameters in a series hybrid are the selection and sizing of the generation and storage devices. Generators can be an ICE/generator pair, a gas turbine generator, fuel cells, or a number of other technologies. Candidates for the accumulator include batteries, ultra capacitors, flywheels, and hydraulic accumulators. Typically, an electric motor is used to provide torque at the wheels. Conventional design methodology for a series hybrid consists mainly of sizing the propulsion motor to provide the desired performance and then choosing a generator and storage device to provide the required range on a specific drive cycle. As previously stated, although the devices chosen to fill those roles might be different, their function remains the same. Thus, a series power plant can be designed based almost entirely on the functional roles and then components can be selected to best meet power requirements.

2.Parallel hybrids

A parallel hybrid design provides considerably more flexibility. Parallel hybrids can be classified into two basic configurations, traction - combining and torque –combining as shown in figure 2. In a traction – combining hybrid, the ICE and the electric motor apply torque separately to different sets of wheels and the torques are combined through the mutual interaction with the road. A typical traction –combining configuration is shown in figure 2, consisting of an ICE and an electric motor connected to two separate axes. Torque –combining drives combine the torques from the ICE and the electric motor before applying them to the transmission shaft. This can be accomplished in two ways, either the ICE and the motor can both be located on the same shaft or they can be located on separate shafts and the torques can be combined through a belt or gearing to the transmission. Both of these configurations are shown in figure 2.

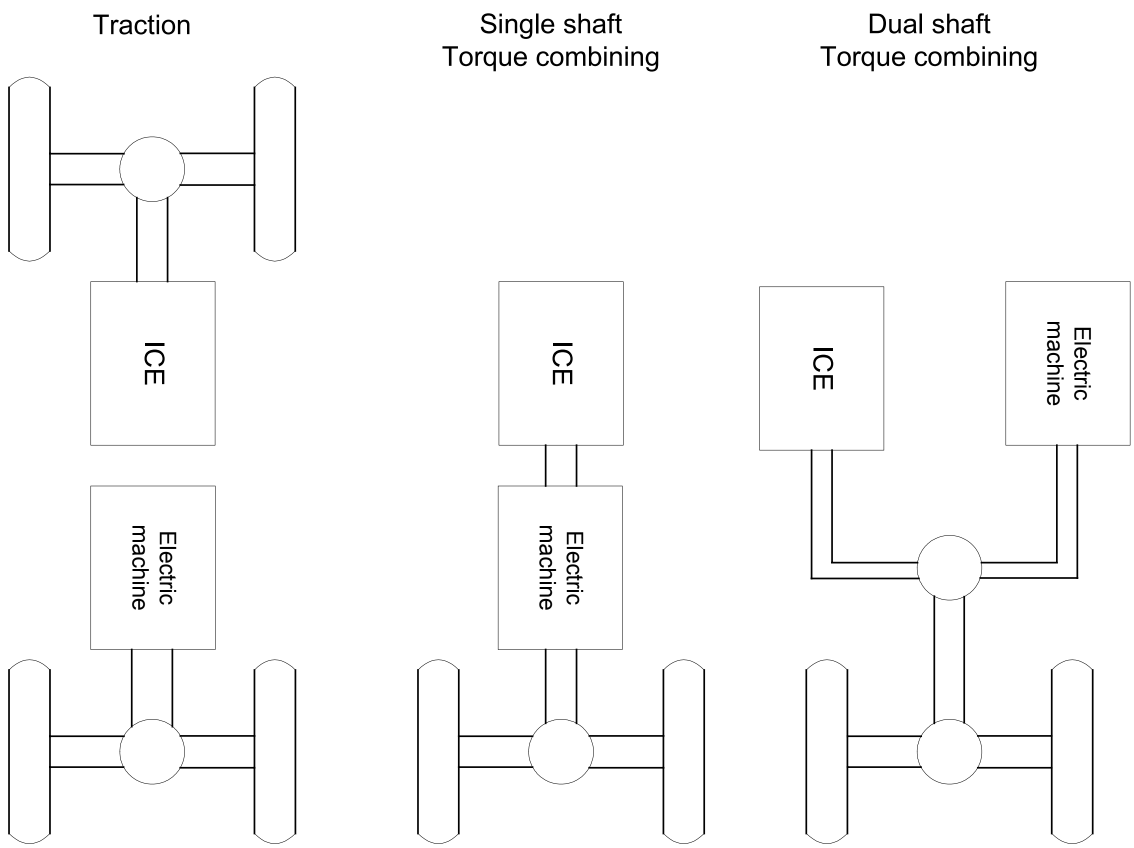


Fig.2. Parallel hybrids.

Given these basic configurations, there are many possible variations, each with different functional roles for the components.

In a typical parallel design, consisting of an ICE and an electric motor in a torque-combining configuration, either the ICE or the electric motor could be considered as the primary energy source depending on the vehicle design and energy management strategy. It is even possible to design a drive train in which the ICE and electric motor are equally responsible for propulsion or each is the prime mover at a certain time in the drive-cycle. A component's functional role might even change within the course of a drive-cycle due to battery depletion or the other vehicle requirements, an option not available in series hybrid designs. Vehicle architecture decisions, component selection and sizing, gearing, and other design parameters become considerably more complex in a parallel hybrid due to the sheer number of choices and their effects on a vehicle's performance for a particular mission.

According to the theory of generalized impedance converters [4], energy converters can be classified into two types; the first type are those, which convert energy from one form to another for example from electrical to mechanical (electric motor). The other types are those, which retain the nature of energy, and just modify its flow. Examples of such type of energy converters would be an electric transformer, a gear coupling, a power electronic converter etc. As stated above, the power train of any vehicle consists of power /energy sources and such converters, which carry the energy from the source to the wheels, such that tractive force is finally applied which results in the motion of the vehicle. Also, energy flow can be uni- directional or bi-directional , depending on the nature of the energy converter.

D. Omni directional design tool concept

Parametric design of a vehicle drive train involves determining the power/energy ratings, sizes, weights etc of all major components in the drive train. These components are sized so as to meet performance requirements like acceleration performance, gradability, gas mileage etc, satisfying constraints like pollution norms, weight and volume restrictions at the same time.

Thus, the design engineer always starts with performance requirements and constraints and work his way towards the sizing of the components, depending on the inter-relation between them. A power train thus designed can be verified for performance by using simulation tools available. This is the conventional method for the parametric design of a power train.

This method of design has a major drawback. It has a sense of direction or flow to it. The design always starts from the performance parameters and proceeds towards sizing the various components. One cannot decide the rating of say the ICE before hand, and then adjust the ratings of the other components, so that the system still satisfies the performance requirements. Such a problem (adjusting the ratings of other components given the rating of one of the components) can be a very complicated job in complex systems like hybrid vehicle power trains, as there are numerous equations relating different components, the performance specifications and the restrictions (mass, volume etc), which have to be handled at the same time. Similarly, the effect of change in the power rating of one component on the others (to meet the performance requirements) is also not always explicit. Suppose, due to space considerations, the motor size needs to be restricted to certain kilowatts. How does this affect the size of the ICE? The battery? The conventional design tool cannot answer such questions explicitly.

It would also be of much help to the designer, if the designer could start his design without having to pick up point inputs or fixed value inputs for his parameters. That is, he just has a fair idea about the value of a certain parameter, which the parameter is within a certain range. He would like to know how this range reflects itself on the output or unknown parameters. Generally, designs always start this way, the designer assumes that certain parameters lie within certain ranges, and then he reduces the range over further iterations of the design till he arrives to a point solution.

It would also be of great help to him if he discovers that for a fixed value of all the inputs, he has a range of values available for a particular output. Then again, he has the choice to reduce that choice to a final point in multiple iterations.

E. Research objectives and thesis overview

The primary objective of this thesis project was to develop a versatile computer design tool to facilitate the design and analysis of series hybrid electric drive trains. This new tool will treat all the performance parameters, constraints, and all the component specifications involved in the design process as 'design variables'. The user will specify as many design variables as he wants to, and the design tool will return the possible values the unknown variables, which might be a single value for a particular variable or might be over a range. Thus, this design tool will not have any sense of direction or flow to it, and the user can start the design process by specifying any of the design variables that he wants. (For example, the user can start by specifying tire radius, battery energy rating, motor base speed, gear ratio, throttle angle of ICE, maximum speed of the vehicle.... and the design tool will calculate the possible values or ranges for all the unknown variables. The results can be plotted as single, two and three dimensional plots in the ‘n’ dimensional design space, where ‘n’ is the number of design variables. The user can study the effect of one variable on the others; he can study trends and even do conventional design if required.

This thesis initially explains the series hybrid drive train in detail, deriving the equations that will be used in the design process. An example of a conventional design is also given in Chapter III. Chapter IV covers the basic algorithm that can be used for any multi-variable complex system. This algorithm will be applied to a series hybrid drive train, and the mathematical validity of the same will be established. The computer software, with the user interface, which implements this design tool will be explained in Chapter V, along with some design examples. Finally, conclusions about the model and recommendations for future studies will be made.

CHAPTER II

SERIES HYBRID ELECTRIC VEHICLES (S-HEV)

A. Introduction

The concept of a series hybrid electric drive train has been developed from the electric vehicle drive train. As mentioned in the previous chapter, electric vehicles suffer from some serious disadvantages, mainly their limited driving range due to limited storage of energy on –board in the form of batteries, limited payload and volume capacity due to the weight and size of the batteries, and also the long time it takes for the batteries to charge. In a series hybrid, an ICE/ Electric generator system is added to the electric vehicle drive train, to charge the batteries on board, and thus increase the driving range.

B. Series hybrid drive train

Although there are many possible configurations for a series hybrid drive train, the most common configuration is shown in figure 3. A traction motor propels the vehicle. The speed torque characteristics of an electric motor are ideally suited for traction. The motor delivers high torque at low speeds and low torque at high speeds. The motor gives a constant torque for variable speed up to the 'base speed' of the motor; beyond the base speed, the torque of the motor decreases with increase in the speed. The torque speed characteristics of the motor are shown in figure 3, and will be discussed in detail in the later chapters. The traction motor is powered by a battery pack and/or an engine generator unit. As can be seen from the figure, the engine generator unit is not directly coupled to the wheels, but supplies its power to the wheels through the electric motor.

Hence, the internal combustion engine, which is the prime mover of the electric generator, can run at a single speed, and give out torque /power is such a way that it always runs at its maximum efficiency region. This region is shown in blue in figure 3. The remaining power required by traction, which might be more or less than the constant power supplied by the engine/generator, is managed by the battery, using an effective control strategy. The types of control strategies will be discussed in later chapters. Operation of the engine in a certain fixed region allows a reduction in the size of the engine as well as better fuel economy as discussed above. The engine/generator unit either helps the batteries to power the traction motor when load power demand is large, or charges the batteries when the load power demand is small. The motor controller is used to control the traction motor to produce the power required by the vehicle. The fuel tank is the unidirectional energy source, while the battery source is the bi-directional energy source. The traction motor can be controlled both as a motor as well as a generator, either in the forward direction or reverse direction. The drive train may need a battery charger to charge the batteries by wall plug – in from the power network. The control strategy is developed in such a fashion that the battery is always charged on board, and thus the driving distance is never limited by the life of the battery. As mentioned previously, the life of the battery is the biggest disadvantage of the electric vehicle, and by charging the batteries on board, this disadvantage is eliminated. The control strategy, which causes the engine to run at a constant torque and speed, is also supposed to ensure that the battery remains charged to a certain level at all time. Hence, the control strategy for the series hybrid and for that matter any type of hybrid is very complex.

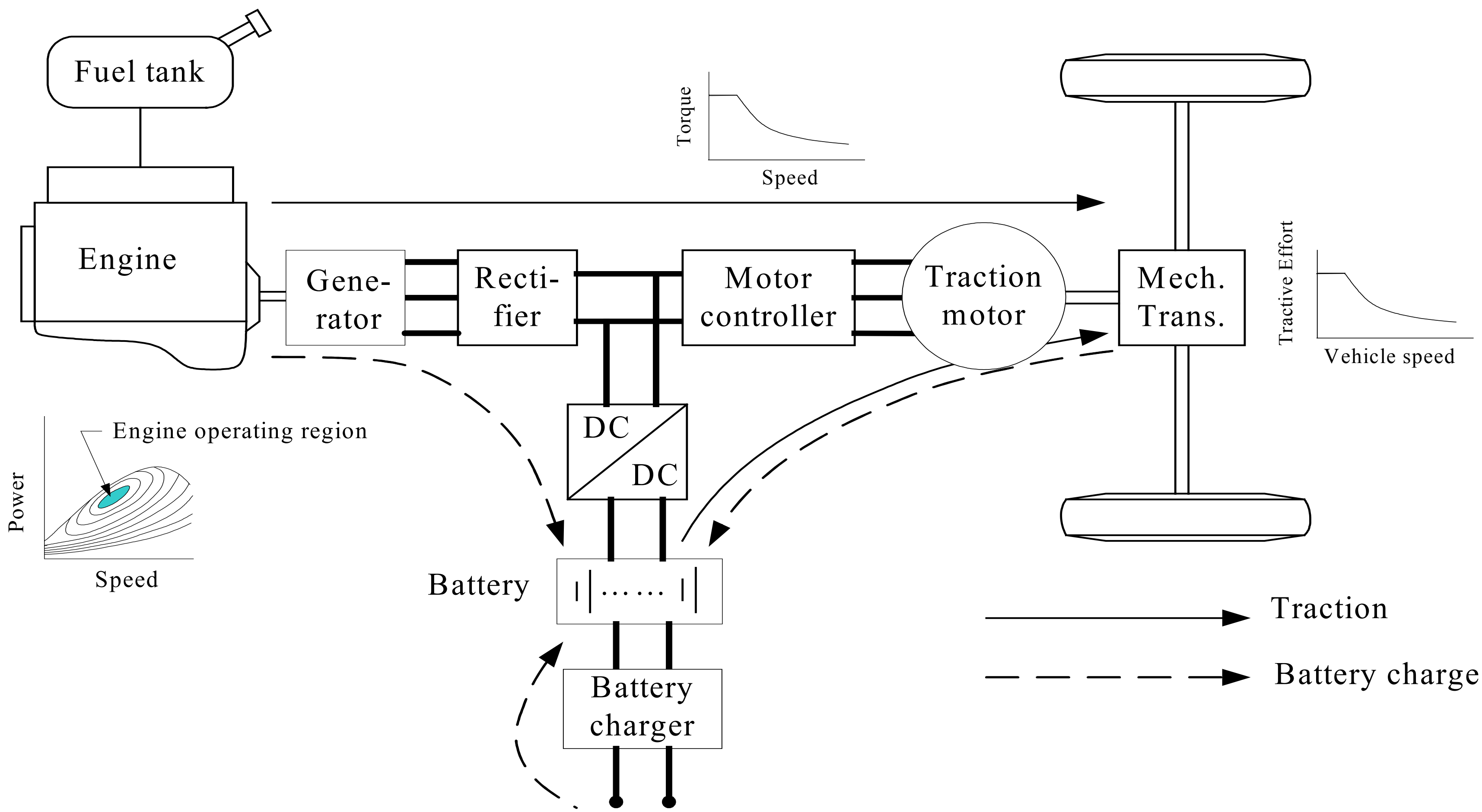


Fig.3. Series hybrid electric drive train.

1.Modes of operation

As seen from the above figure, the engine/generator system is mechanically decoupled from the drive wheels. The speed and torque of the engine is independent from the vehicle speed and demanded traction, and hence can be controlled to any operating point on its speed torque plane. Generally, the engine should be controlled such that it always operates in its optimal operation region, in which the fuel consumption and the emissions of the vehicle are minimized (figure 4). Due to the mechanical decoupling of the engine from the drive wheels, this optimal engine operation is realizable. However, it heavily depends on the operating modes and the control strategy of the drive train. The drive train has several operating modes, which can be selectively used according to the driving condition and the desire of the driver.

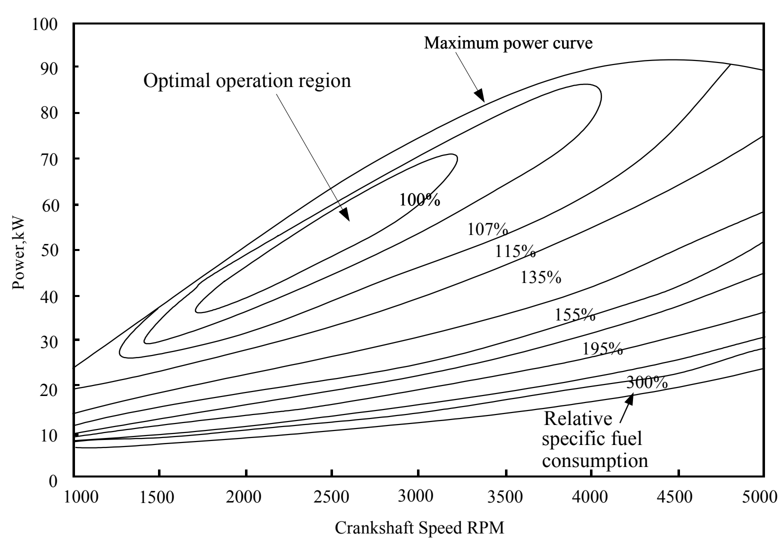


Fig.4. Engine characteristics and optimal operating region.

1.Pure electric mode: the engine is turned off and the vehicle is propelled only from the batteries.

2. Pure engine mode: the vehicle traction is derived only from the engine-generator, while the batteries neither supply nor draw any power from the drive train. The electric machine serves as an electric transmission from the engine to the driven wheels.

3. Hybrid Mode: the traction power is drawn from both the engine-generator and the batteries.

4. Engine traction and battery charging mode: the engine-generator supplies power to charge the batteries and to propel the vehicle.

5. Regenerative braking mode: the engine-generator is turned off and the traction motor is operated as a generator. The power thus generated is used to charge the batteries.

6.Battery charging mode: The traction motor receives no power and the engine – generator charges the batteries.

7. Hybrid battery charging mode: Both the engine-generator and the traction motor operate as a generator and charge the batteries.

C. Control strategy

The operation of the series-hybrid drive train is controlled by various controllers (figure 5), which, depending on the inputs, command the operation of each component of the drive train. The controllers receive the operation commands from the driver, and feedback from the drive train components and decide which of the above operational modes are to be employed. A good control strategy is very important for optimal performance of the drive train. A good control strategy ensures that the engine runs at its optimal efficiency point for most of the drive cycle, and that the battery state of charge is maintained through out the drive cycle. It is imperative that the battery does not discharge over a certain distance, otherwise, the hybrid vehicle would be like an electric vehicle, and would suffer from the same disadvantages that led to the failure of the electric vehicle. The disadvantage would be that of limited range possible with a single journey, as the battery would get discharged and the vehicle would have to be forcibly stopped.

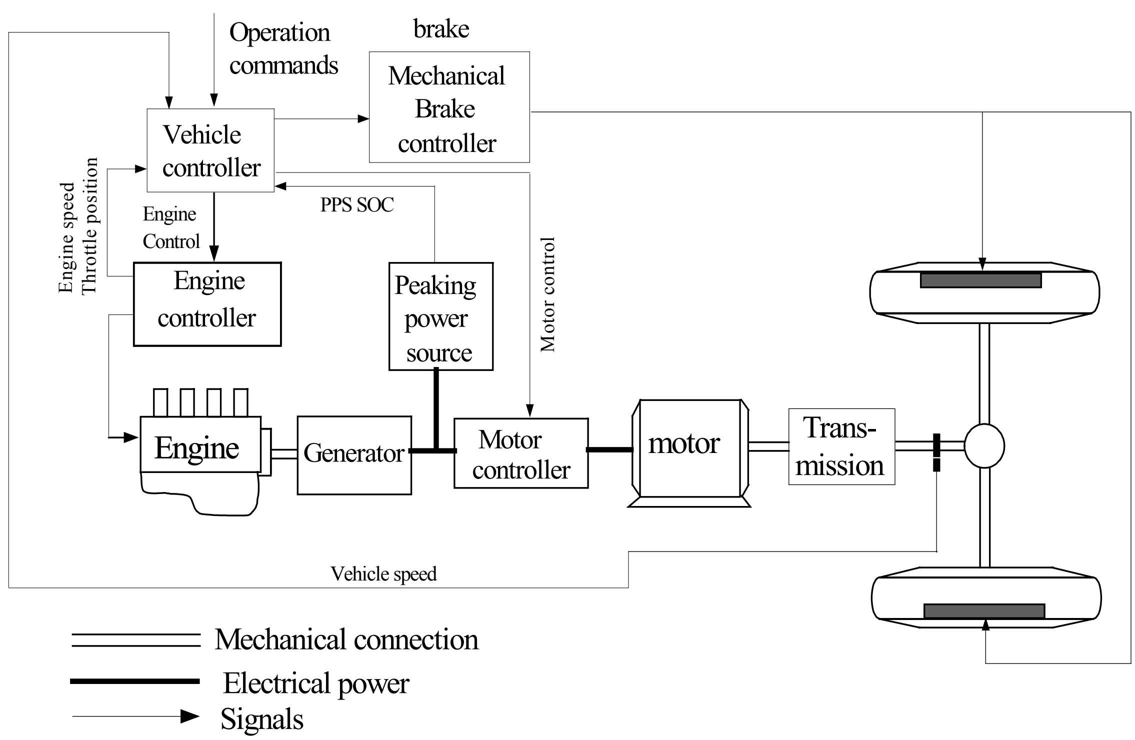


Fig.5. Series hybrid electric power train with the various controllers.

Two typical control strategies are introduced here [5].

1. Maximum State of Charge of Peaking Power Source (figure 6).

2.Engine Turn-on and Turn-off (Engine – on-off) Control strategy (figure 7).

1.Maximum state of charge of peaking power source control strategy

The aim of this control strategy is to maintain the state of charge of the peaking power source throughout the drive duration, and meet the necessary traction requirements at the same time.

This strategy has been explained with the help of figure 6, wherein points A, B, C, D represent the power demands in either traction or braking.

Consider Point A. The demanded power is more than what the engine/generator alone can meet (Pe/g). Hence the motor supplies the extra power to meet the load demand. (Ppps).

At point B, the power required is less than the power produced by the engine /generator at its optimal operating point. In this case, this surplus power that is being produced by the ICE can either be used to charge the peaking power source (if the SOC of the peaking power source is less than the value at which it has to be maintained) else the engine is operated in its non-optimal region, to supply just the traction power.

Point C has negative (braking power) which is more than the braking power that the motor can alone produce, hence hybrid braking is used. Here, the electric motor produces its maximum braking power and mechanical brakes are also applied in addition.

Point D represents the commanded braking power that is less than the maximum braking power that the motor can produce. In this case, only regenerative braking is used.

2.Engine turn on and turn off

This control strategy is particularly useful on highways, where the maximum SOC control strategy is rendered ineffective, as the peaking power source can easily be charged to its maximum on a highway, and then, the engine has to operate at sub-optimal regions of operation (figure 7).

In this control strategy, the operation of the engine-alternator is completely controlled by the SOC of the peaking power source. When the SOC reaches its preset maximum, the ICE is turned off and the vehicle is propelled by the peaking power source alone. When the SOC reaches its preset minimum, the engine/generator is turned on. The

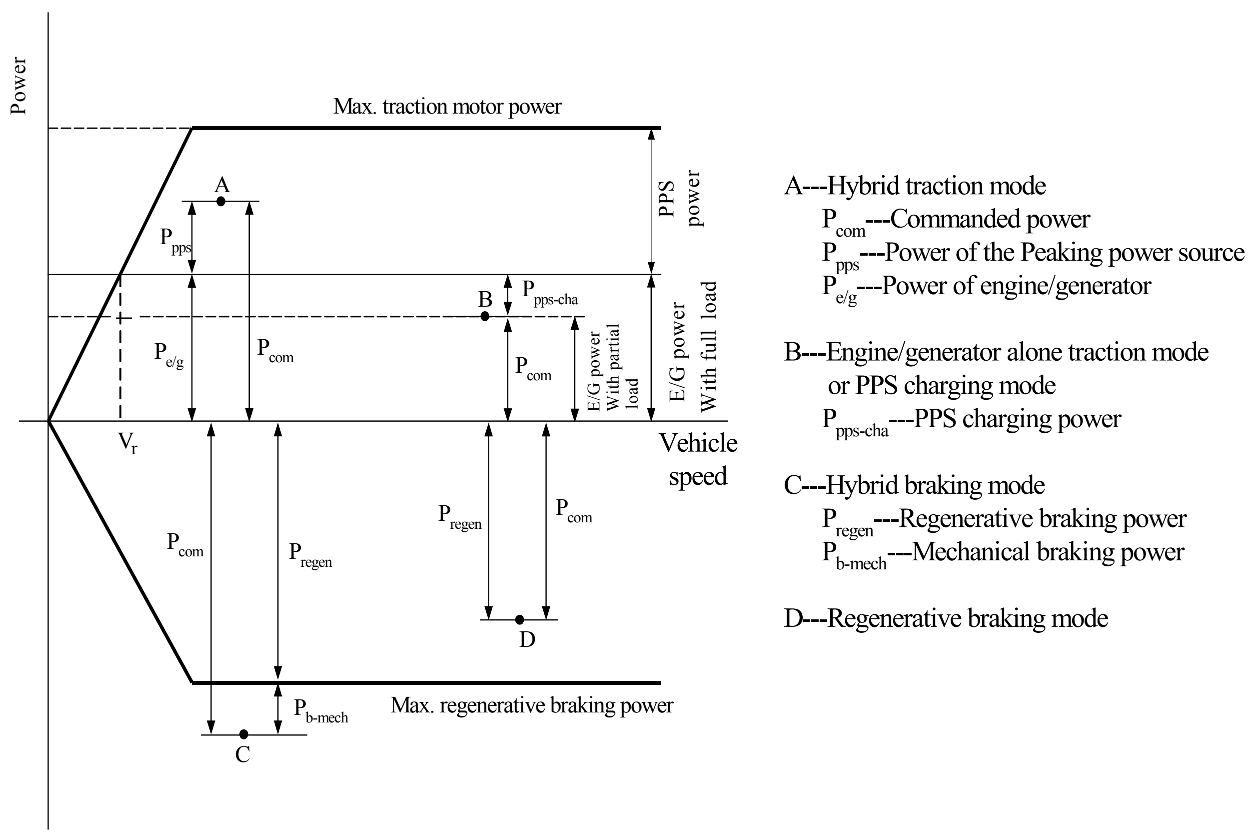


Fig.6. Maximum SOC control strategy.

peaking power source is charged by the engine/generator simultaneously, thus enabling the engine/generator to always operate in its optimal operating region.

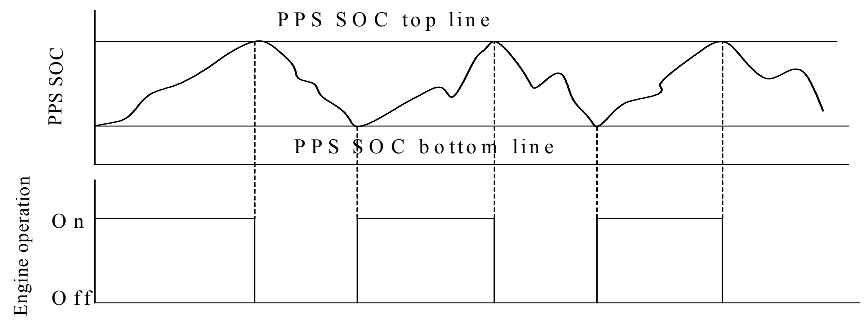


Fig.7. Engine turn on and turn off control.

D. Equations related to major components

As discussed in Chapter I, parametric design of the drive train involves sizing the major components for power/energy rating, mass, size etc. The power rating of these components is determined so that the vehicle is able to meet its performance requirements using one of the control strategies stated above or some other control strategies.

The equations, which are used to determine the power ratings of these components, are discussed below. A detailed derivation of these equations involves study of vehicle dynamics [6], electric motors and power converters [7], ICE modeling [8], battery model [9] and others.

1.Traction motor

(1) Traction motor characteristics: As shown in figure 8, the motor has a constant torque

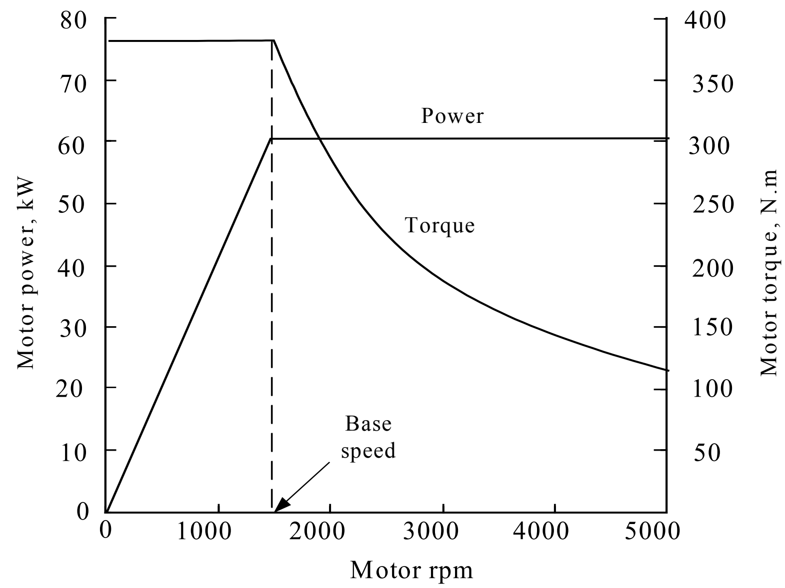


Fig.8. Speed torque characteristics of a traction motor.

region till base speed, beyond which there is constant power region.

The ratio of maximum speed of the motor to its base speed is called the factor ‘x’. As shown in figure 9, with increase in the values of ‘x’, the maximum torque of the motor also increases for the same power, thus increasing the acceleration and gradability performance (higher acceleration- higher torque; higher gradability – higher torque) and also simplifies the transmission.

$$x = \frac{Motor\max imumvelocity}{Motorbasevelocity}$$

(2) Motor power rating: The power rating of electric motor drive in series HEV is completely determined by the vehicle acceleration requirements, motor characteristics and transmission characteristics.

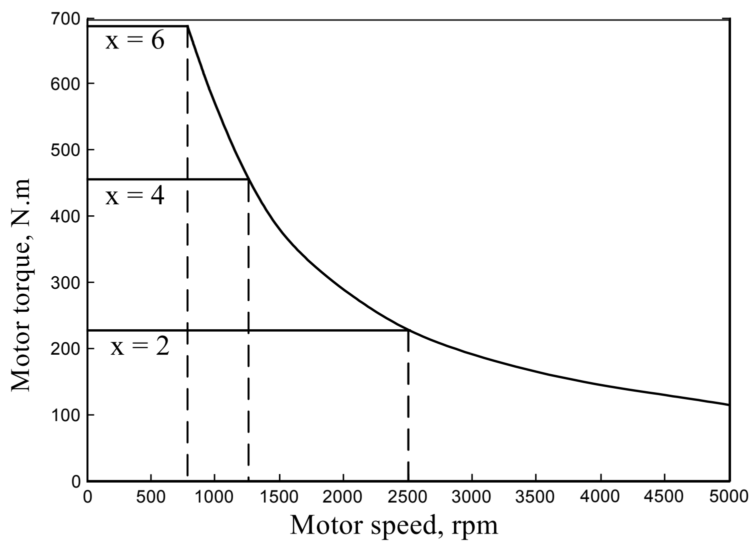


Fig.9. Speed torque characteristics of a 60HP motor for x=2, 4 and 6.

The motor might have been derived either from the peaking power source or the energy source; it is always equal to the tractive power. Tractive power can be defined as the power being delivered to the wheels at any instant [12]. The power rating of the traction motor can be represented as shown below [10].

$$P_t = \frac{\delta M_v}{2t_a}(V_f^2 + V_b^2) + \frac{2}{3} M_v g f_r V_f + \frac{1}{5} \rho_a C_D A_f V_f^3$$

where

$P_t =$ Traction motor power in watts.

M_v = Total vehicle mass in kg.

t_a = Expected acceleration time in seconds.

V_f = Final speed of the vehicle accelerating in m/s.

V_b = Vehicle base speed in m/s.

g = Gravitational acceleration in m/s.

f r = Tire rolling resistance coefficient.

ρ_a = Air density i.e. 1.202 kg/cubic meters.

C_D = Aerodynamic Drag Coefficient.

A_f = Vehicle front area.

2. Engine/generator

As discussed earlier, the engine/generator in a series hybrid drive train is used to supply the steady-state power, in order to prevent the peaking power source from being discharged completely. While calculating the power of the engine/generator, two conditions should be considered, one is driving for a long time with constant speed, such as highway driving between cities, and other is the driving with frequent stop-go driving pattern, such as driving in the cities. In the long distance driving pattern, the drive train should not rely on the peaking power source to support the operation at a certain high speed, say 130 km/h or 80mph. The engine generator should be able to provide enough power at this high speed. For the stop-go pattern, the engine/generator should provide sufficient power to maintain the energy storage of the peaking power source at a certain level, so that enough power can be drawn to support the vehicle acceleration.

At constant speed and on flat road, the power output from the power source can be calculated as [10]

$$P_{e/g} = \frac{V}{1000\,\eta_t\,\eta_m}\left(M_v\ g\ f_r + \frac{1}{2}\rho_a\ C_D\ A_f\ V^2\right) \quad (kW)$$

where

η_t, η_m are the efficiencies of the transmission and motors respectively.

When the vehicle is driving in the stop and go pattern in urban areas, the power that the engine/generator produces should be equal to slightly greater than the average load power in order to maintain the PPS energy storage balanced. This load can be given by

$$P_{ave} = \frac{1}{T}\int_0^T \left(M_v\ g\ f_r + \frac{1}{2}\rho_a\ C_D\ A_f\ V^2\right) V\ dt + \frac{1}{T}\int_0^T \delta\ M_v \frac{dV}{dt}\ dt$$

where T is the total drive cycle time.

When designing for a stop and go type of system, the power capability should be greater than that needed to support the vehicle at constant speed as well as the average power required in urban areas (figure 10). In any hybrid vehicle, due to the limitations of the battery, it is never possible to absorb all the regenerative power. This is because this power is in the form of high current for a very short time (impulse power). The battery can take in only a certain amount of power in a given period of time. Similarly, the power intake is also limited by the power electronics of the traction motor. Hence, figure10 shows the average power with full regenerative braking and partial regenerative braking; the average power with partial regenerative braking is in between the average power with full and no regenerative braking. This is the power that the engine must be able to provide.

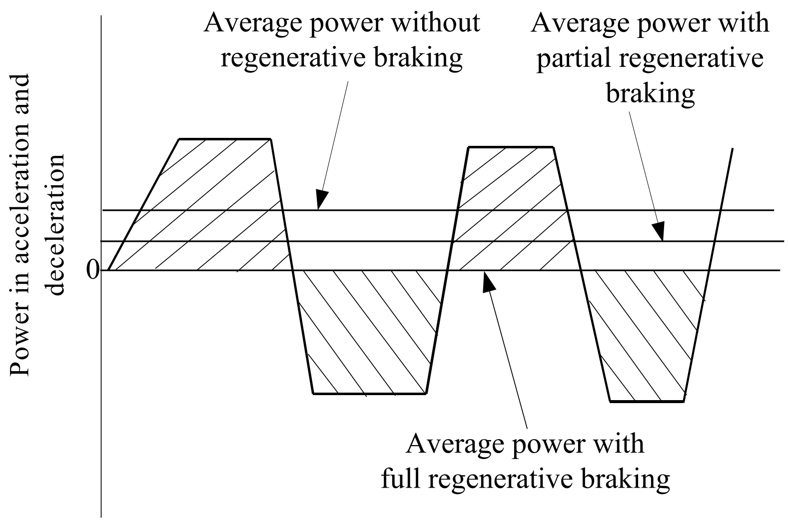


Fig.10. Average and instantaneous tractive power versus time.

Throughout this thesis, we have considered the engine and the generator to be a single entity, and will be considered as the energy source for the power train.

3.Peaking power source

The peaking power source and the engine/generator jointly supply power to the traction motor, which finally provides power to the wheels. Therefore, the total power of the engine/generator and the peaking power source should be greater than or at least theoretically equal to the power of the electric motor.

If $P_{m,\max}$ is the power rating of the traction motor, $P_{e/g}$ is the engine/generator power and η_m is the efficiency of the motor, then the PPS (Peaking power source) power rating can be calculated as

$$P_{pps} \geq \frac{P_{m,\max}}{\eta_m} - P_{e/g}$$

4.Drive cycle

In order to help with the simulation, design and analysis of power train, certain typical driving schedules have been developed. These driving schedules represent typical traffic environments for a particular range of time. The drive cycle is a plot of velocity versus time. Some typical drive cycles along with the average and instantaneous tractive powers are shown in figure 11.

5.Energy rating of peaking power source

In transportation, the unit of energy is usually kWh (kilo-watt-hour) rather then J or kJ (joule or kilo-joule). The energy consumption per unit distance in kWh/km is generally used to evaluate the vehicle energy consumption. However, for ICE vehicles, the commonly used unit is a physical unit of fuel volume per unit distance, such as liters per 100km (L/100km). In the USA, the distance per unit volume of fuel is usually used (miles per gallon, mpg). On the other hand, for battery powered EVs, the original energy consumption unit in kWh, measured at battery terminal is suitable, because the battery energy capacity is usually measured kWh, thus the driving range per battery charge can be easily figured out. Similar to ICE Vehicles, L/100km (for liquid fuel) or kg/100km (for gas fuel, such as hydrogen) or miles per gallon or miles per kilogram gaseous fuel may be suitable. It will be seen that this assumption is suitable for hybrids and simplifies the calculations.

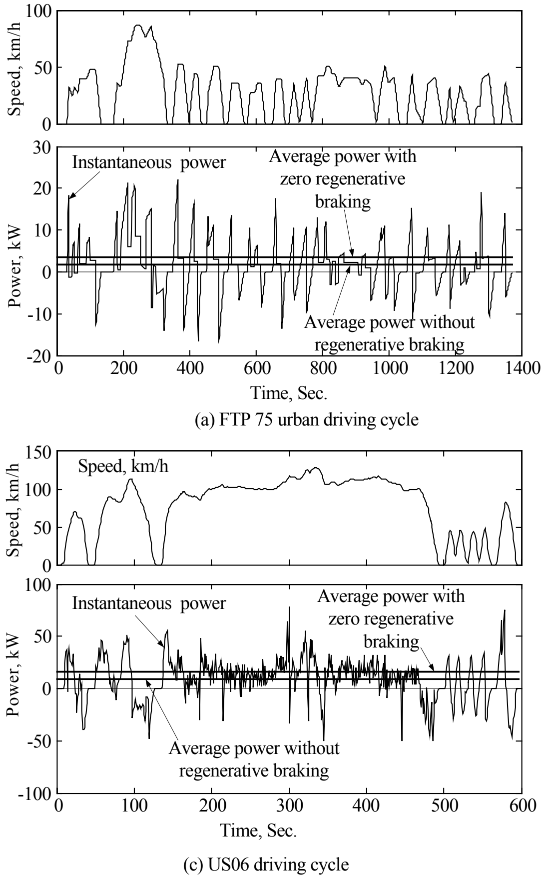


Fig.11. Instantaneous power and average power with full and zero regenerative braking in some typical driving cycles.

When the peaking power source is a battery, as in the case used for this thesis, the original energy consumption unit of KWH is preferred. Energy consumption is the integration of the power output at the battery terminal.

The peaking power source supplies power intermittently in any drive cycle, and the power supply from the PPS is controlled by the controller, depending on the control strategy. The energy changes in the peaking power source can be expressed as

$$\Delta E = \int_0^T P_{pps} \, dt$$

Where, P_{pps} is the instantaneous power from the peaking power source. This might be positive, zero as well as negative (charging of the peaking power source). The changes in the energy level of a peaking power source for an entire drive cycle is shown in figure 12.

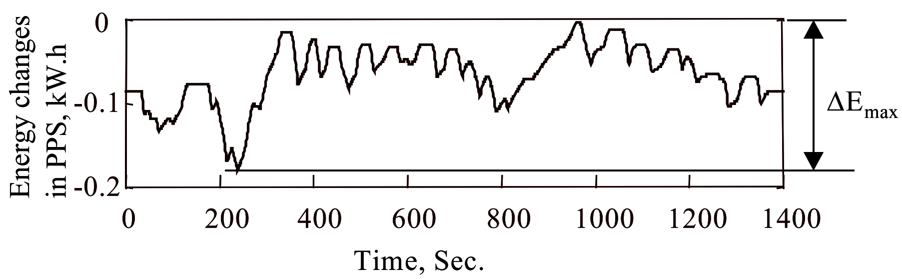


Fig.12. Variation in PPS energy over a drive cycle.

6.State of charge

State of charge is a very important term used in the case of a battery. State of charge of a Battery is defined as the ratio of the present charge of a battery to the maximum charge that can be possibly stored in a battery. A fully charged battery would have a state of charge as 1 while a completely discharged battery would have a state of charge at zero. Generally, the variation in the state of charge is limited to a certain range during the battery operation. This is because, the battery charging efficiency is very poor at high state of charge and the discharge efficiency is poor at very low state of charge (figure 13).

Knowing the maximum variation in SOC that has been set in the control algorithm, and knowing the maximum variation in energy for a particular drive cycle, the energy rating of the battery can be decided by using the formula

$$E_{cap} = \frac{\Delta E_{\max}}{SOC_{top} - SOC_{bott}}$$

Where

E_{cap} = Energy capacity of the peaking power source.

ΔE_{mxa} = The maximum variation in energy over a typical drive cycle.

SOC_{top} = Maximum SOC of the peaking power source.

SOC_{bott} = Minimum SOC of the peaking power source.

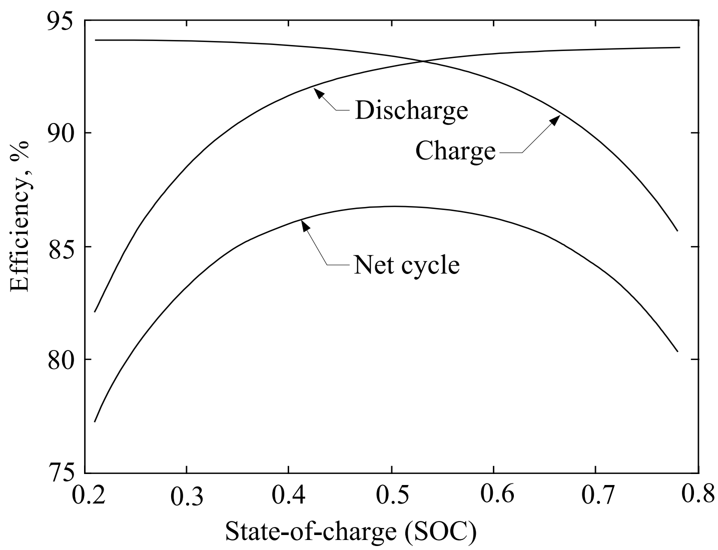


Fig.13. Variation in charging and discharging efficiencies with state of charge.

7.Transmission

The power delivered to the wheels in the case of a series hybrid comes entirely from the traction motor. The speed torque characteristics of a motor are ideally suited for traction. The speed torque characteristic of a motor has two regions (figure 9) the constant torque region and the constant power region. The constant power region shows high torque at low speed and low torque at high speeds. Since the torque speed characteristics of the motor match ideally with that of the traction requirements, an electric motor is much better suited for traction as compared to an I.C. Engine. The Speed torque characteristics of an IC engine are not suitable directly for traction, hence a gearbox has to be used, which shapes the torque at various speeds and makes it suitable for traction. In the case of a series hybrid, a single gear transmission between the traction motor and the wheels is possible, since it uses electric motor for traction.

The mechanical torque generated by the motor is translated to the torque at the wheels by a gear. The torque at the wheels can be represented as a product of force exerted by the wheel on the ground (also known as tractive effort) and tire radius. (figure 14). Figure 15 shows the plot of tractive effort versus speed.

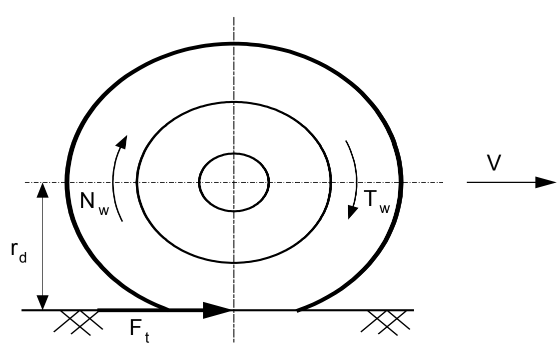


Fig.14. Torque at the wheels and the tractive effort (Ft).

Tractive effort can be derived from the following equation.

$$F_t = \frac{T_p \, i_g \, \eta_t}{r_d}$$

where

F_t = Tractive effort;

i_g = Gear ratio.

η_t = Transmission efficiency

r_d = Tire radius.

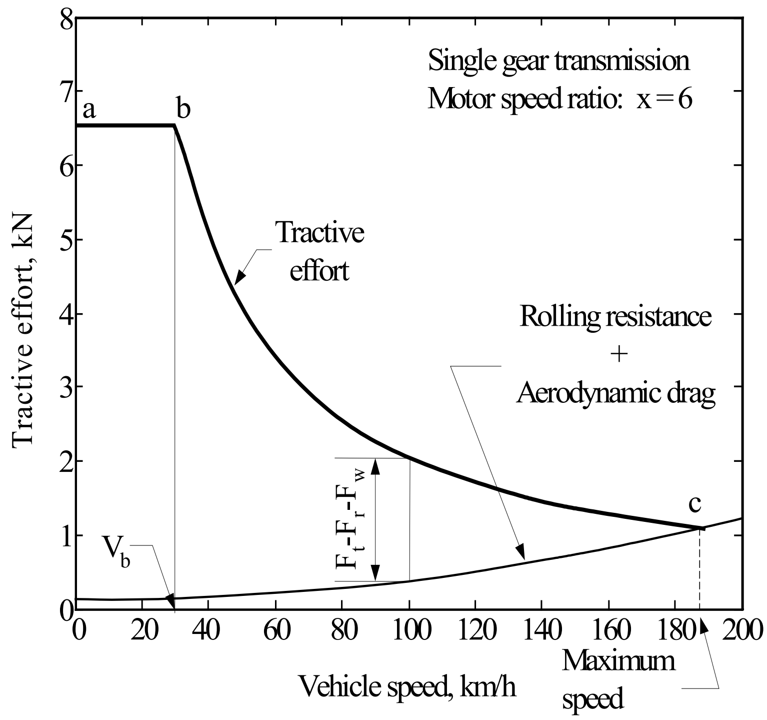


Fig.15. Tractive effort versus speed for a traction motor of x = 6.

Tractive effort is an important parameter in designing the gradability of the vehicle. At a given speed, the resistance offered by the vehicle for a particular gradient (α) is given by

$$F_t = \frac{T_p\, i_g\, i_0\, \eta_t}{r_d} = M_v\, g\, f_r \cos\alpha + \frac{1}{2}\rho_a\, C_D\, A_f\, V^2$$

The gear ratio is designed such that the vehicle reaches maximum speed at the motor maximum speed, that is

$$i_g = \frac{\pi\; n_{m,\max}\; r}{30\; V_{,\max}}$$

where

i_g = Gear ratio.

$n_{m,\max}$ = Maximum speed of the motor.

$V_{,\max}$ =Maximum vehicle velocity in m/s.

r = tire radius .

E. Summary

This chapter discusses the basic theory, which is used in system level design of a series hybrid. The main components have been identified and their characteristics are defined. The important equations relating the components to the performance characteristics, as well as inter-relating the components have been presented. The next chapter will give an example of a conventional design process for system level design of a series hybrid drive train.

CHAPTER III

CONVENTIONAL DESIGN OF A SERIES HYBRID ELECTRIC VEHICLE

A. Introduction

As stated in Chapter I, the conventional design method involves designing all the power train parameters given the performance specifications like acceleration performance, gradability and the constraints like maximum weight, pollution norms, fuel consumption and so on.

In chapter II, the basic components of a hybrid drive train, which will be considered for the design purpose, were introduced. Equations relating these components to each other as well as the performance specifications and the constraints were presented.

In this chapter, a conventional design of a series hybrid electric will be carried out, so that the comparison between the following process as well as that followed by the omni-directional design method can be appreciated.

B. Design example

1.Design specification

Here, the performance specifications, as well as other parameters will be provided before hand.

Parameters:

Vehicle total mass	1500 kg.
Front area of the vehicle (A_f)	2.0 square meters.

Transmission efficiency (Single Gear)	90%
Traction motor drive efficiency	85%
Generator efficiency	90%
Aerodynamic drag coefficient (C_D)	0.3
Rolling resistance coefficient (f r)	0.01
Tire radius	0.3 meters
Air density (ρ_a)	1.202 kg/square meters
Performance specifications	
Acceleration time (from 0 to 100 km/h)	10 Seconds
Gradability	more than 5% at 100 km/h.
Maximum speed	160 km/h.

Note that in a conventional design, all the above parameters have to be provided before the design process starts.

We now use the equations mentioned in the previous chapter to design the various components of the series hybrid.

2.Design of traction motor

The power rating of the traction motor is determined by using the equation

$$P_t = \frac{\delta M_v}{2t_a}(V_f^{\,2} + V_b^{\,2}) + \frac{2}{3} M_v\, g\, f_r\, V_f + \frac{1}{5}\rho_a C_D A_f V_f^{\,3}$$

In this case, we know that

M_v = Vehicle mass = 1500 kg.

t_a = Acceleration time in seconds = 10 seconds.

V_f = Final Speed of the Vehicle in m/s = 160 km/h.

V_b = The final speed corresponding to motor base speed.

As discussed in Chapter II, the motor base speed and the maximum speed of the motor are related by a factor 'x'.

$$x = \frac{Motor\,\max mumvelocity}{Motorbasevelocity}$$

The factor 'x' is arbitrarily chosen to have a value of 4.

As the motor and the wheels are connected to each other by a single gear transmission, the ratio between the motor maximum speed and base speed is also reflected on the vehicle side, the ratio between maximum vehicle velocity (V_f) and V_b will be 'x' = 4.

The Motor power thus calculated will be 82.5 KW. Hence the value of V_b can be calculated. The values of C_D, A_f, f, ρ_a have already been specified. The motor maximum speed is chosen to be 5000 RPM. Correspondingly the motor base speed is 5000/4 that is 1250 RPM.

Knowing the motor power and the motor base speed, the rated torque of the motor is calculated. (Motor power = Motor base speed × Rated motor torque). The motor torque thus calculated is found out to be 630 Nm.

Thus the specifications of the traction motor are as follows (figure 16):

Motor power	82.5 KW.
Motor rated torque	630 Nm.
Motor base Speed	1250 RPM.
Motor maximum Speed	5000 RPM.

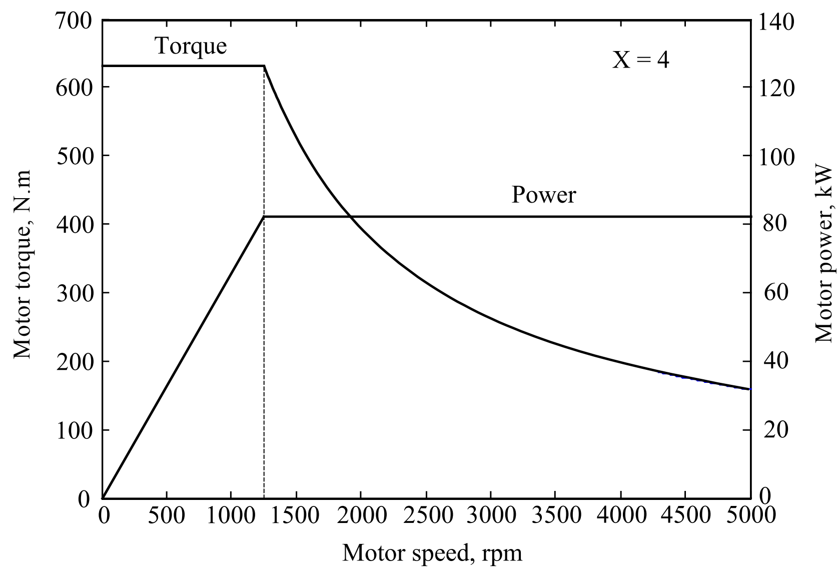


Fig.16. Speed torque and speed power curve for the designed traction motor.

3.Design of gear ratio

As is the case of an electric vehicle, the traction motor is connected to the wheels through a single gear ratio. The reason for this being the speed torque characteristics of a motor, which are ideal for traction. Hence the gear ratio is designed such that the vehicle maximum speed corresponds to the motor maximum speed.

$$i_g = \frac{\pi \ n_{m,\max} \ r}{30 \ V_{\max}}$$

where

$n_{m,\max}$ = Maximum motor speed = 5000 RPM.

r = tire radius = 0.3 meters.

$V_{\max}$ = 160 km/hr.

The gear ratio thus calculated is 3.29.

As said in the previous chapter, the gradability and the acceleration performance of the vehicle entirely depend on the traction motor rating and the gear ratio. Reference [12] gives a method to calculate the acceleration performance from the physics of the vehicle. Using the derivations made in Reference [12], the acceleration time as well as the distance covered after acceleration can be plotted against vehicle speed (figure 17).

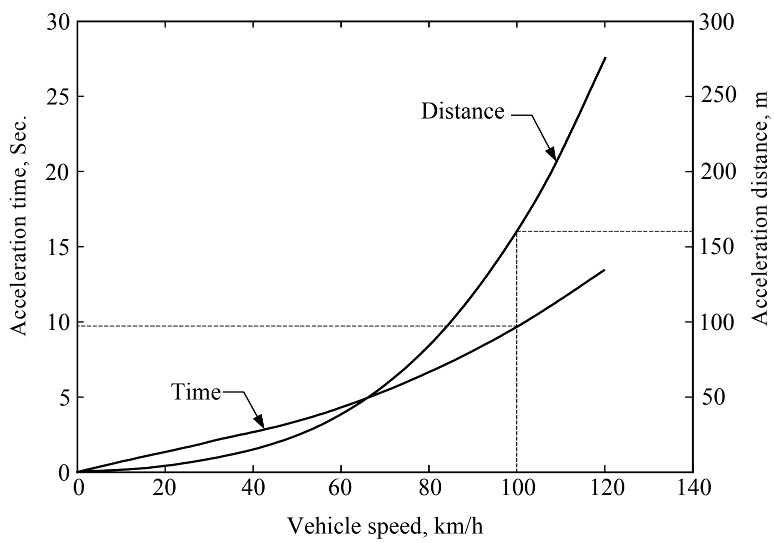


Fig.17. Acceleration performance.

To check if the motor is able to meet the gradability condition, the tractive effort of the vehicle is plotted with the vehicle resistance (aerodynamic drag + rolling resistance + the hill climbing) (figure 18). Observe that the tractive effort possible at a speed of 100 km/hr is more than enough to overcome a grade of 5%.

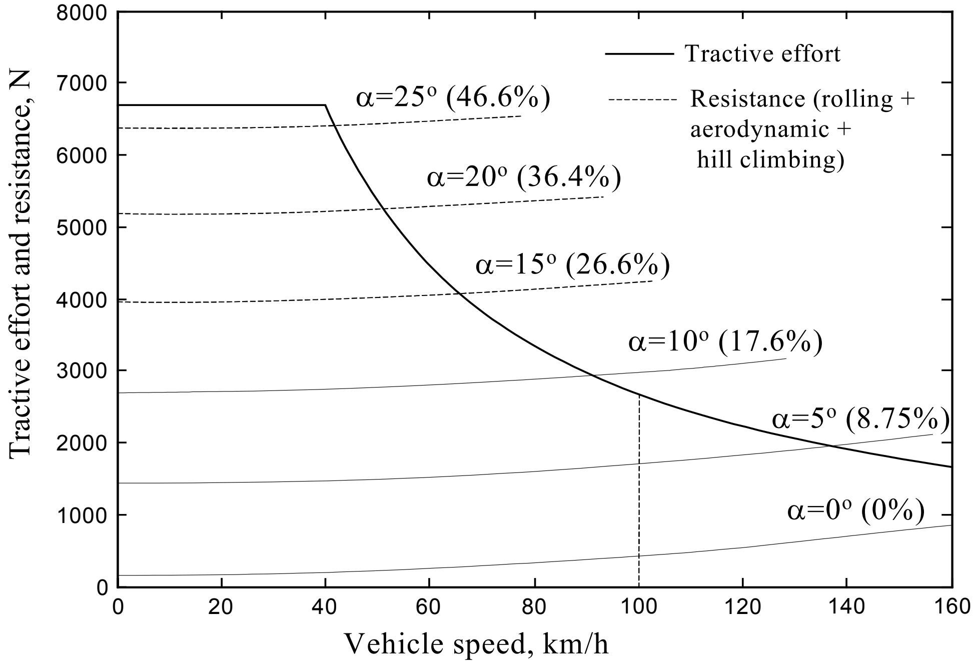


Fig.18. Traction effort and resistance of vehicle versus vehicle speed.

4.Design of engine/generator

The engine generator is rated such that it supports the vehicle at regular highway speed (80 mph) on a flat road. Considering a 5% grade, the engine power needed to support the vehicle at this speed, considering transmission efficiency to be 90%, motor drive efficiency to be 84% and the generator efficiency to be 90% is around 32.5 KW.

Thus, this engine/generator will be able to support the vehicle when traveling long distance on a highway at a constant speed of about 80 miles/hr. It is also needed to be verified that this engine/generator will be able to maintain sufficient energy in the peaking power source when used for the urban or the stop and go type of traffic. Under such driving conditions, the engine/generator is supposed to supply the average power over the drive cycle. Table 1 provides data about average power needed for various drive cycles.

Table 1: Average power with full and no regenerative braking for different drive cycles

	Max. speed km/h	Average speed km/h	Average power with full regen. braking (kW)	Average power with no regen. braking (kW)
FTP75 urban	86.4	27.9	3.76	4.97
FTP75 highway	97.7	79.6	12.6	14.1
US06	128	77.4	18.3	23.0
ECE-1	120	49.8	7.89	9.32

Note that the engine with a power rating of 32.5 KW will be able to maintain the energy of the peaking power source easily in the case of an urban stop and go type of driving.

5.Power rating of peaking power source

The traction power is provided to the wheels by the traction motor. The traction motor is powered by the two power sources, the peaking power source and the engine/generator. Naturally, the sum of the power ratings of the peaking power source and the engine/generator should be greater than or equal to the input power of the traction motor. Since the power rating of the engine/generator and the traction motor has been decided, the rating of the peaking power source can be easily calculated.

$$P_{pps} = \frac{P_{motor}}{\eta_{motor}} - P_{e/g} = \frac{82.5}{0.85} - 32.5 \times 0.9 = 67.8\ kW$$

6.Design of the peaking power source energy capacity

The energy capacity of the peaking power source is completely designed by using the drive cycle and the control strategy.

For this design the engine-on and off control strategy is chosen. As written in the earlier chapter, the state of charge is chosen to vary over a given range. The S.O.C is decided to vary from 0.6 to 0.4. Hence $SOC_{top} - SOC_{bott}$ = 0.2. The drive cycle FTP 75 is chosen for simulation. Also, the energy capacity of the PPPS is decided to vary from 1.5 KWH to 1 KWH (figure 19). Hence ΔE_{mxa} = 0.5 KWH. Having decided how much the state of charge as well as the energy rating of the peaking power source, its energy capacity can be calculated.

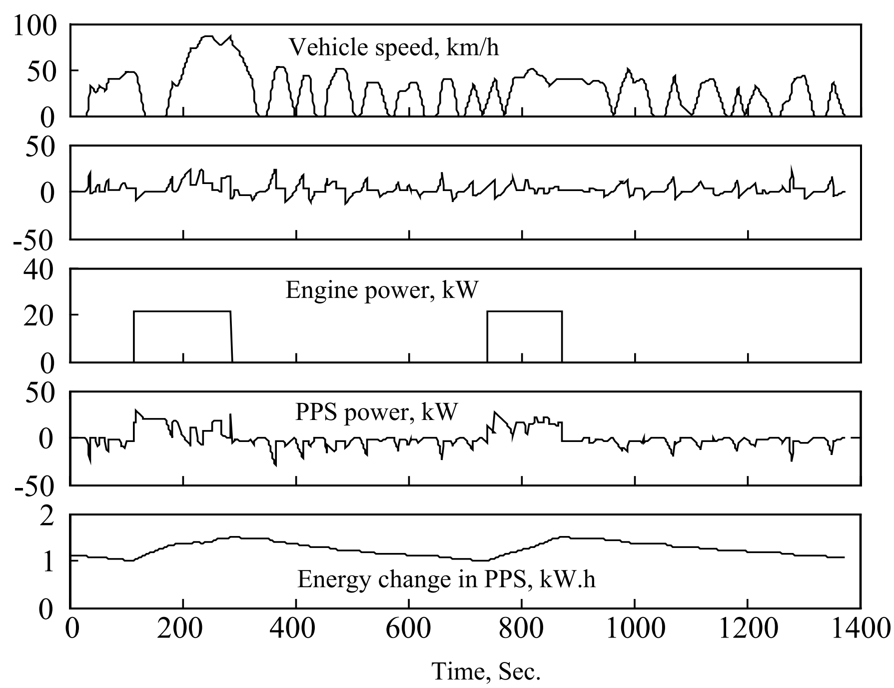


Fig. 19. Simulation results for the given engine and the PPS rating.

$$E_{pps} = \frac{\Delta E_{mxa}}{\Delta SOC} = \frac{0.5}{0.2} = 2.5\ kW.h$$

7. Fuel consumption of the ICE

The operating point of the Internal Combustion Engine is shown in figure 20 below. From the plot of the fuel consumption, we understand that for the engine power of 35.5 KW (considering all the efficiencies) and the generator power of 30 KW, the brake specific fuel consumption (b.s.f.c) is 270-grams/kilo watt hour. Total fuel consumption over the drive will be obtained by integrating the product of the b.s.f.c and the engine power over the complete drive cycle.

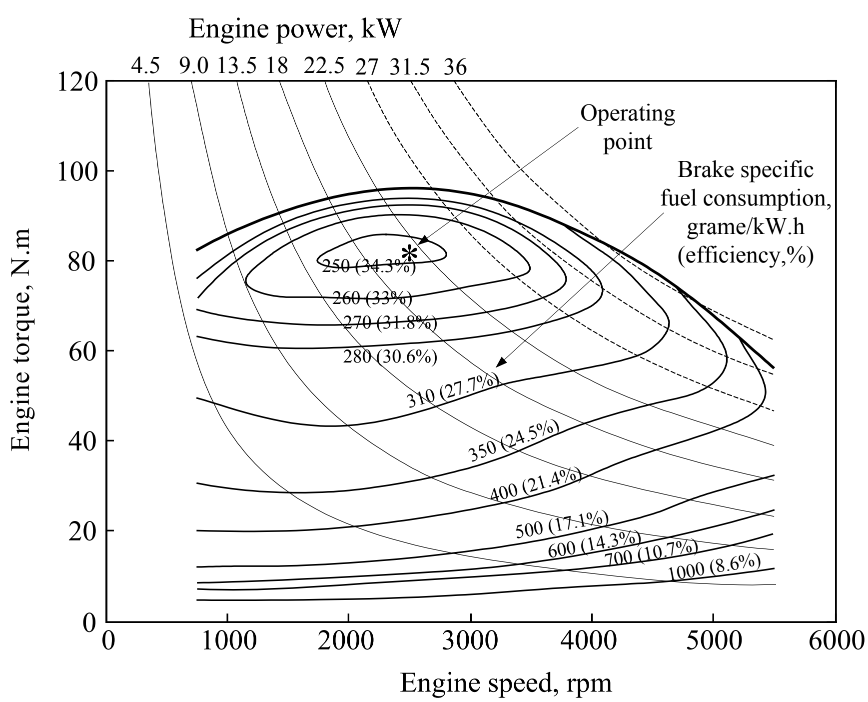


Fig.20. Operating point of the internal combustion engine.

$$Q_t = \int_0^T (P_e g_e)/(3600 \times 1000)\, dt$$

where

P_e = Engine power in kW.

g_e = Brake specific fuel consumption in grams/KWH.

T = total time of the drive cycle.

$$Q_L = \frac{100{,}000\, Q_t}{\gamma\, S} (Liters / 100km)$$

And the miles per gallon can be calculated as

$$mgh = \frac{S / 1.6 \times 1000}{\frac{Qs / \gamma}{3.87}}$$

Where S is the total distance the vehicle travels in the whole driving cycle in meters and γ is the fuel mass per liter in kg/liter. The fuel economy thus calculated is 5.12 Liters/100 km or 46.6 miles/gallon.

C. Summary

In this chapter, a series hybrid electric vehicle was designed according to the conventional methods. The power ratings of the major components were calculated as per the equations discussed in chapter II. In the next chapter, the theory behind the omni-directional design concept will be laid out.

CHAPTER IV

CONCEPT OF OMNI-DIRECTIONAL DESIGN TOOL

A. Introduction

In the last chapter, a series hybrid driver train was designed according to conventional design methods. In this chapter, the concept behind the new design tool will be established. This new concept offers us many more freedoms, which can be used for better design and better insight into the system.

B. The new approach

The variables of a series hybrid electric vehicle, which have been considered for this exercise along with the major components, are shown in figure 21.

1.Conventional design

The flow the design in the conventional method of design is pre-determined; it goes from the performance specifications to the other components as shown in figure 22.

The conventional design process looks at the problem of design from a physical perspective; each variable has its won distinct identity; it has its characteristics, importance and in a conventional design, is always calculated in a specific way. For example, acceleration is a performance specification, while gear ratio is a physical variable. For design, acceleration has to be defined before hand; other wise conventional design is not possible. The gear ratio will be calculated from the maximum velocity of the vehicle and that of the motor. You always start with the performance specifications and work towards the parameters.

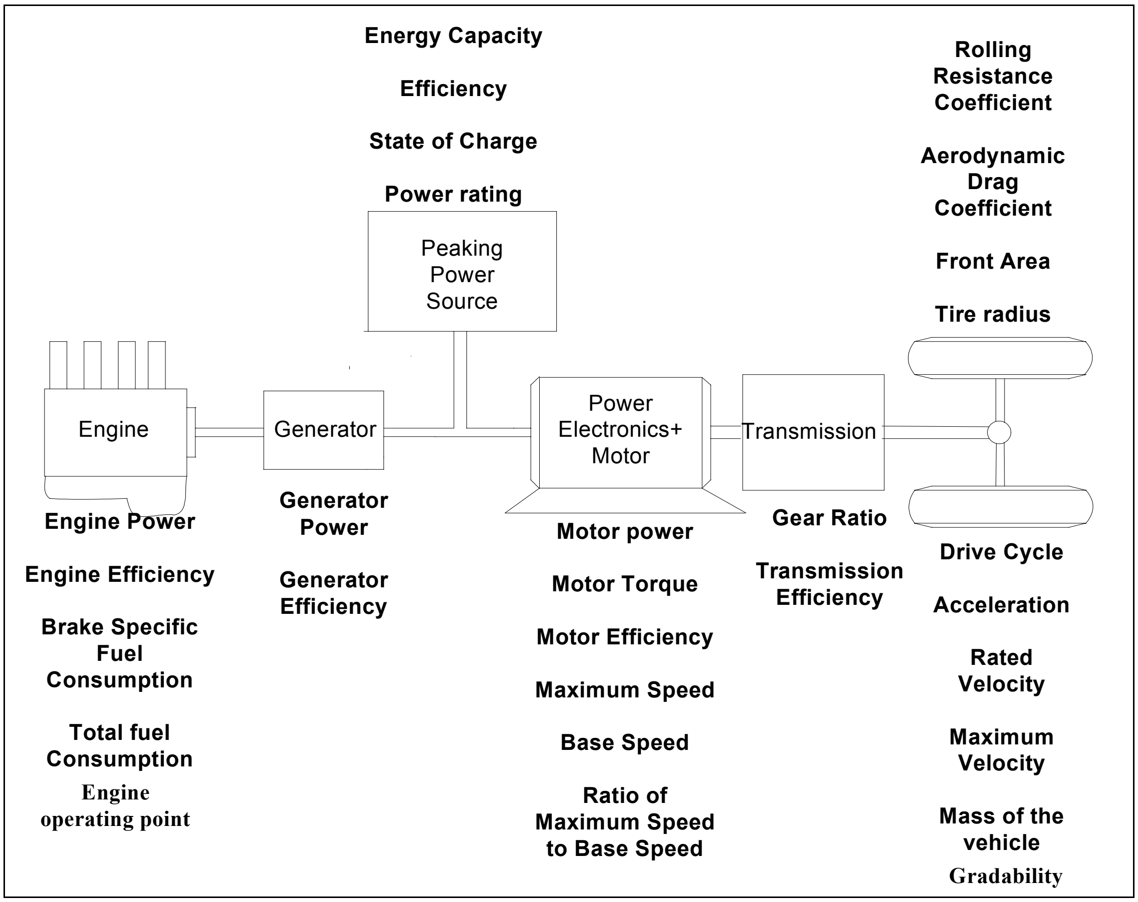


Fig.21. Variables of a series hybrid considered for design.

There have been attempts to look at the problem of parametric design from a different perspective. Chandrasekaran et al [13], look at several possible design scenarios. A range of values for certain parameters or components is chosen at the beginning, resulting in a large number of designs to start with. Each design candidate is the tested against a 'design critic', which evaluates the design for a particular aspect of performance. Designs, which fail certain criteria, are filtered out. A concept called 'Dominance Filtering' is also used which compares one design to the other and removes eliminates the design, which is inferior with respect to that criterion. The surviving designs are be studied by plotting the variables of the surviving designs against each other, in the form of two or three-dimensional plots.

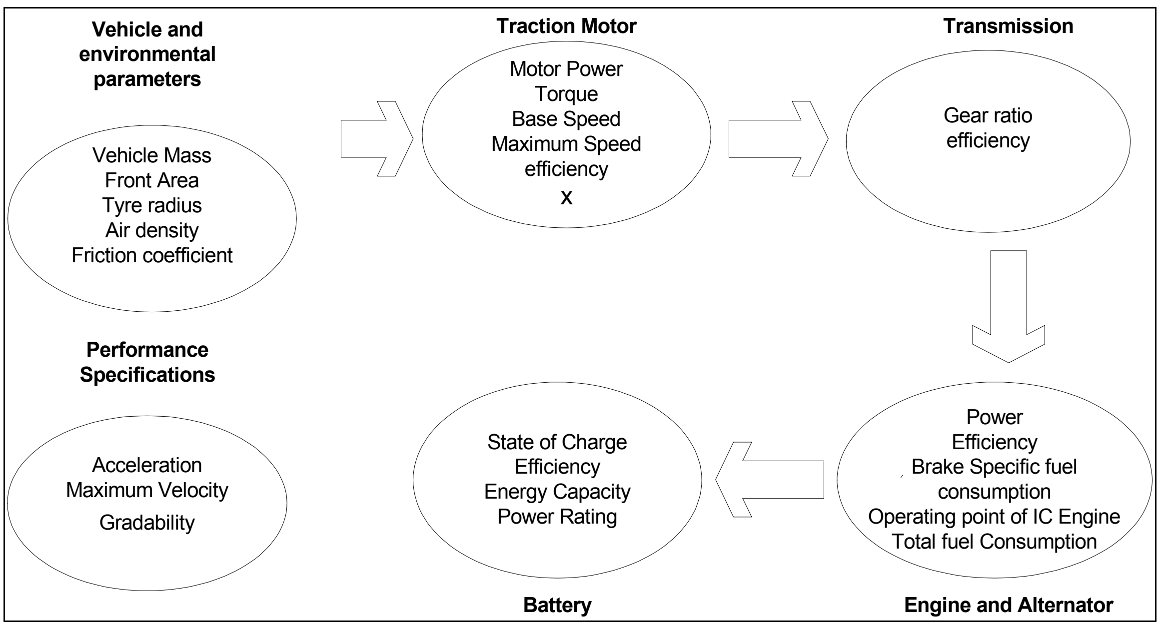


Fig.22. Flow of the design procedure in a conventional design process.

A major drawback of this approach is that fact that it requires a lot of computational power, and hence a lot of time to arrive at the final result. This approach is hence possible with many computers or a super computer etc available for this purpose.

2.A new approach to design

Before associating the word ‘omni-directional’ with hybrids, we shall consider two simple scenarios.

Consider the following two equations

$$x + 2y = A$$
$$x - 3y = B$$

A unidirectional algorithm for simultaneous equations will always consider A and B as ‘parameters’ of the system and will only be able to solve for ‘x’ and ‘y’. It will not be able to solve for A and B given ‘x’ and ‘y’ nor will it be able to solve for a combination of A and ‘x’ or ‘y’. Similarly, it will be unable to solve for B and ‘x’ or ‘y’.

On the other side, an omni –directional tool will be able to solve for any two unknowns from the set of four variables A, B, x, y; provided two have been specified at a given time. There is another facet to the omni directional design tool. Consider the circuit given in figure 23 below.

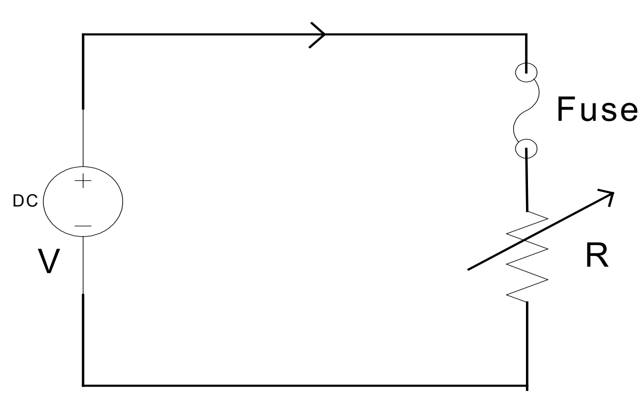


Fig.23. A DC voltage source with a variable resistive load.

The figure shows a DC voltage source with a variable resistor as a load. The circuit also has a fuse. The mathematical equation to describe this circuit according to Kirchoff' S voltage law would be

$$I = V/R$$

Where

I = current flowing through the circuit.

V= voltage applied.

R= value of the variable resistance.

Voltage and resistance are defined as the input or the known parameters and the current is the unknown parameter.

Now consider the following scenarios:

1. Voltage and resistance are single value (point) inputs.

Naturally, the current would be a point (single) value. Voltage, resistance as well as current are plotted as single dimensional plots, i.e. the value of the parameter is plotted on a number line as shown in figure 24(a).

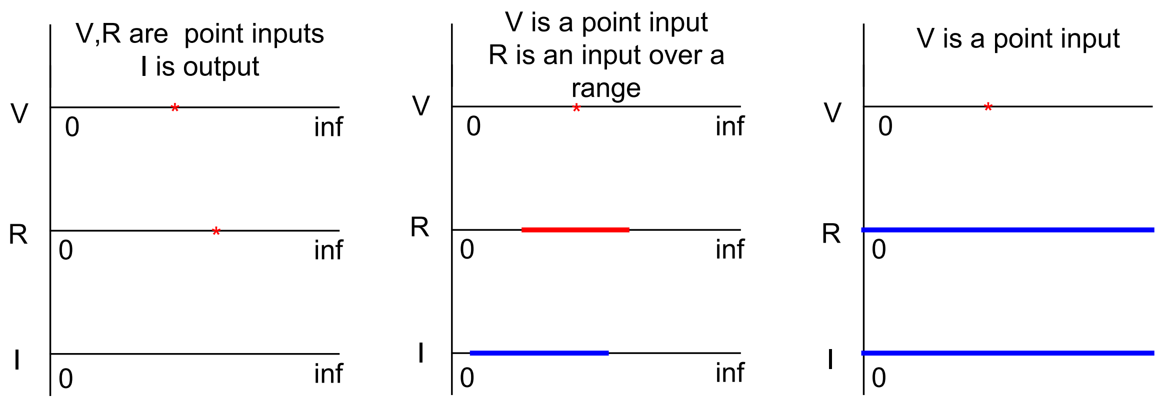
The DC voltage source can only supply voltage with the polarity shown in figure 23 and hence the direction of current is also fixed which is considered as positive current. Therefore, axes for the single dimensional plots (figure 24) (the number line) extends from 0 to positive infinity.

2. Voltage is a point input while the resistance varies over a finite range (Resistance is a range input).

In this case, as the resistance varies over a finite range, the output value (current) also varies over a finite range as shown in figure 24(b).

3. Only voltage has been specified as the input.

If just the voltage has been specified as the input, then for a resistance value, which can vary from zero to infinity, the current varies from infinity to zero. Thus, for an under specified system, the outputs have an infinite range (figure 24 (c)).



(a) (b) (c)

Fig.24. Single dimensional plots of the V and R as well as the output I.

The result of the third scenario is obtained by looking at the equation I=V/R. But, there is a physical aspect to this system, which will not allow the outputs to have a range varying from 0 to positive infinity in the third scenario. This physical aspect is the fuse present in the system. The fuse restricts the maximum value of current possible in the circuit. This in turn, dictates the minimum resistance that is possible.

Considering the physical aspects, the 3rd scenario can be represented as shown in figure 25.The first two scenarios are examples of point input – point output and range input – range output scenarios. The third, as shown in figure 25 below, is an example of point input – range output scenario. It is interesting to note that if just the mathematical equation is considered, then the case shown in figure 24(c) is encountered. But, because the mathematics is associated with a physical system (which in this case is a electric circuit with a fuse), a unique phenomenon of point input finite range output is observed. For the above example, this scenario manifested itself when the inputs were under specified. But, as will be seen in the case of the hybrid vehicle design problem, this scenario can also manifest itself due to other reasons.

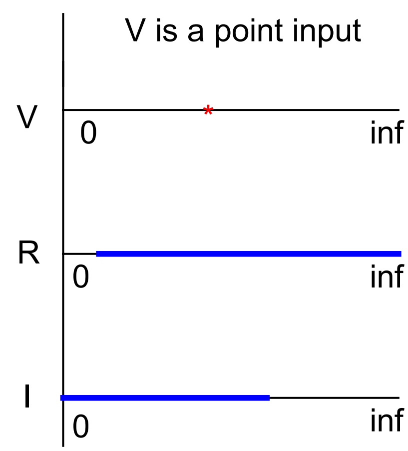


Fig.25. Example of a point input – finite range output scenario.

In the case of this omni – directional tool, the scenario can be interpreted in the following fashion. Depending on the inputs selected by the user, he might encounter a range for certain outputs for given point inputs. In such a case, the user has the freedom to choose any value from that output range and still be assured that his inputs are still the same. This gives him new freedoms, which will be elaborated later with examples. Identifying such point in range out scenarios requires in depth knowledge of the system.

The above two scenarios, the first that of omni –directional design and the second one of point input range output scenarios are the two main facets of the tool and the new contributions towards parametric design of systems.

In the omni –directional design philosophy applied to a HEV, the performance parameters, all the component parameters, the constraints etc are equivalent as far as the design is concerned, and can be referred to as ‘design variables’. The equations that relate all the design variables together are referred to as design equations. The user can specify any of the design variables that he knows or are of importance to him, and the unknown design variables are calculated by solving the design equations and considering the physical restrictions. The challenging part is in the fact that the physical restrictions are not present for each and every design scenario, but they turn up for some scenarios and does not for others. Also, depending upon the design inputs and the values of those design inputs, the physical restrictions vary. Hence, before starting to write the program for the design process, it is very necessary to consider and take into account all such scenarios possible. If the system is such that there are many variables that are tightly coupled to each other then many such scenarios might exist and developing a logic that takes care of all such scenarios might be a difficult proposition. But, as will be observed in the case of this particular case, the scenarios are very easily discernable. So, the algorithm for the omni – directional design will vary with the system.

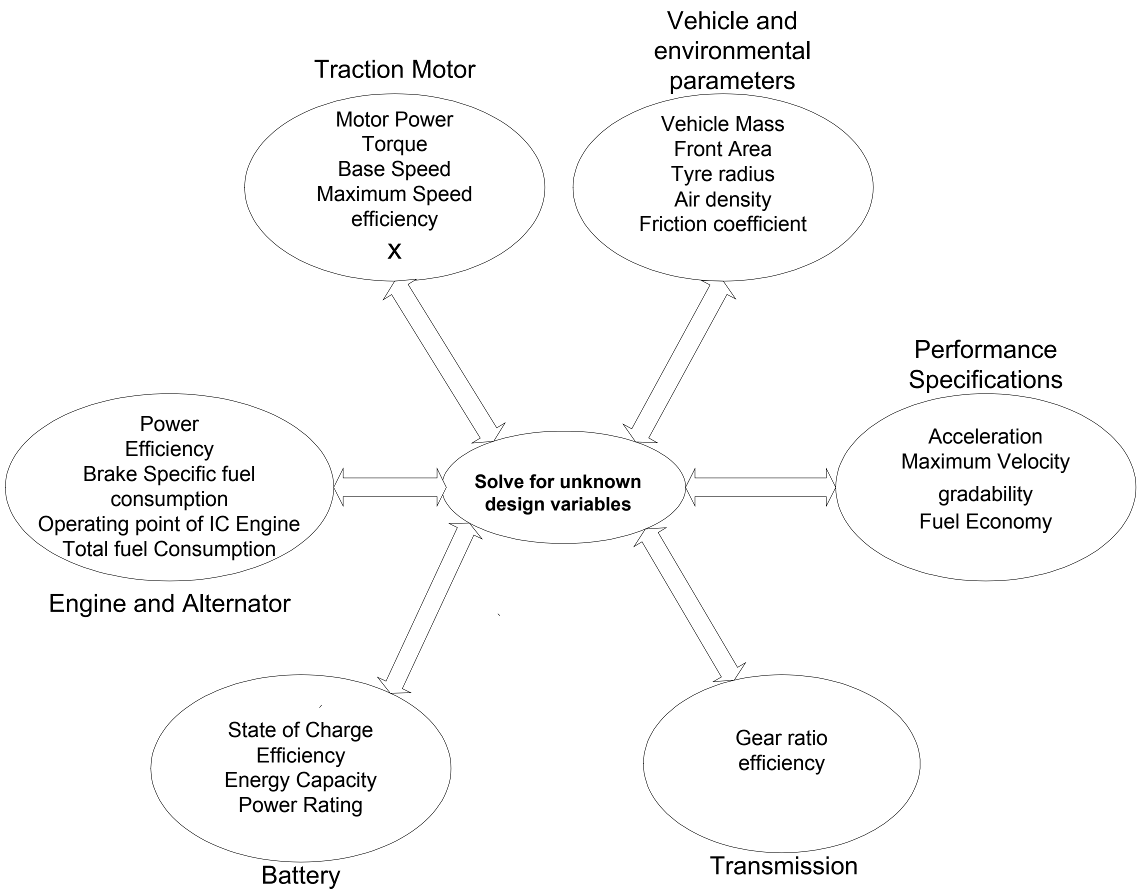


Fig.26. Flow of design according to the new design method.

Note that in this method, there is no ‘flow’ as such to the design (figure 26). Any of the variables can be selected as the starting point. In the earlier design approach (fig 22) as well as the design example was presented in the earlier chapter, the performance specifications had to be specified before hand. With the new design approach, the performance specifications can be a part of the result; the design algorithm can be stated from somewhere else.

C. Exploiting the new approach

Before proceeding with the algorithm behind the new approach, it is important to discuss the value of this approach. It is worthwhile having such a tool only if the new freedom attained by this tool can be utilized to enhance the design process and look at it from a new dimension. Following are some applications of the new design tool, which are possible due to the freedom of choosing the input and the output variables.

1.Start anywhere

As mentioned in the previous section, the user can start with any of the design variables as input variables.

A).Starting from another component

Therefore, the entire design could be started from another component itself. For example if the design engineer knows some motor parameters, he can start of with those as the input parameters and the parameters of every other sub-system can be calculated (Figure 27). Starting with the traction motor, the performance characteristics will be a part of the output variables, and this is very useful in cases where the effect of motor size and motor parameters on the vehicle performance is to be studied. Similarly, the effect of battery, gear ratio on the performance parameters can be studied. This could not have been done with the conventional design tool, as we could not have gone from the motor to the performance characteristics. Similarly, we can have another component to start with and see its effect on the performance parameters.

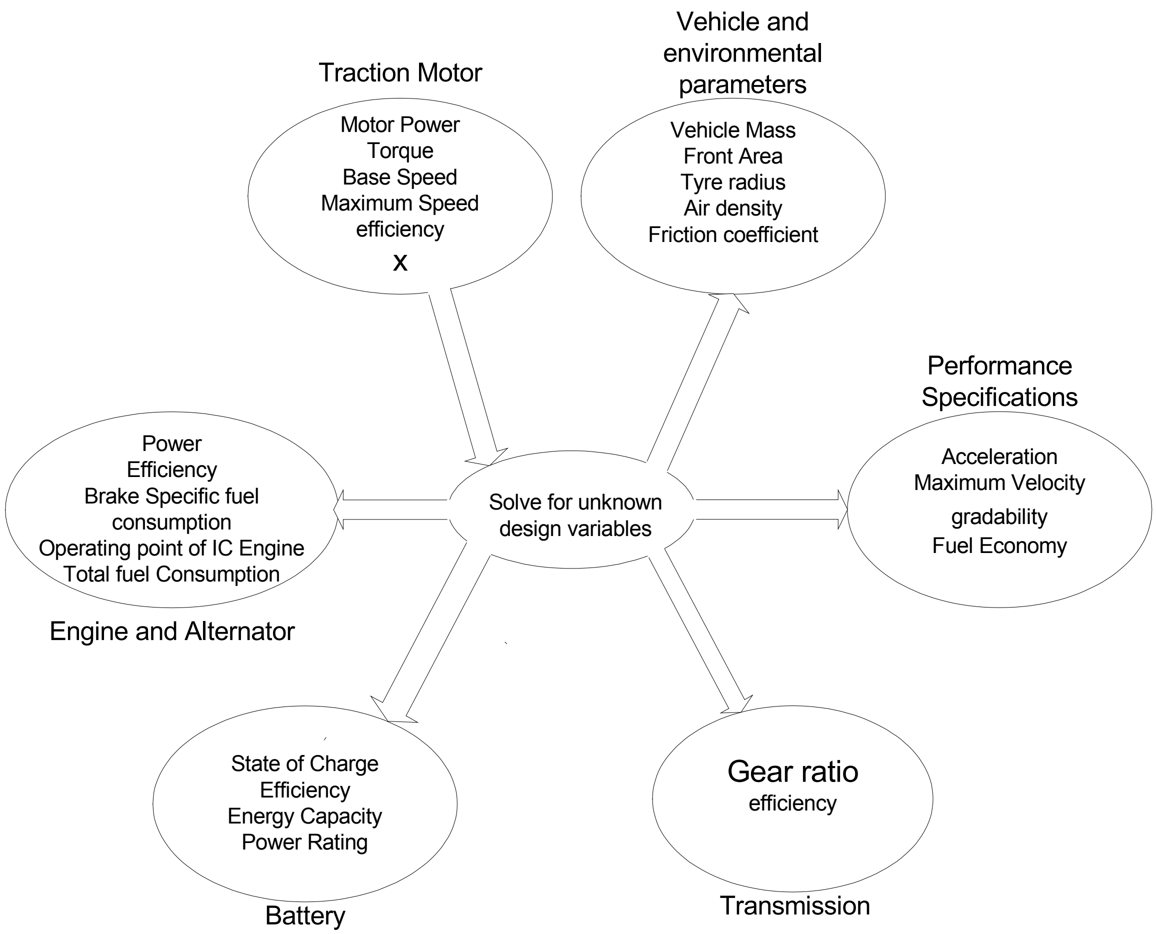


Fig.27. Starting the design with the traction motor.

B).Starting from some parameters from each component

In this scenario (figure 28), some parameters of each component can be specified; there might be some components where nothing is specified. This scenario is important if the design engineer wants to ensure that the values of some parameters are kept fixed, while others might vary. For example, he might want to keep the base speed and maximum speed at certain preset values, as he is fixing the nature of the motor, and he does not mind other parameters to vary. This design tool will help him to design the vehicle keeping these things in mind.

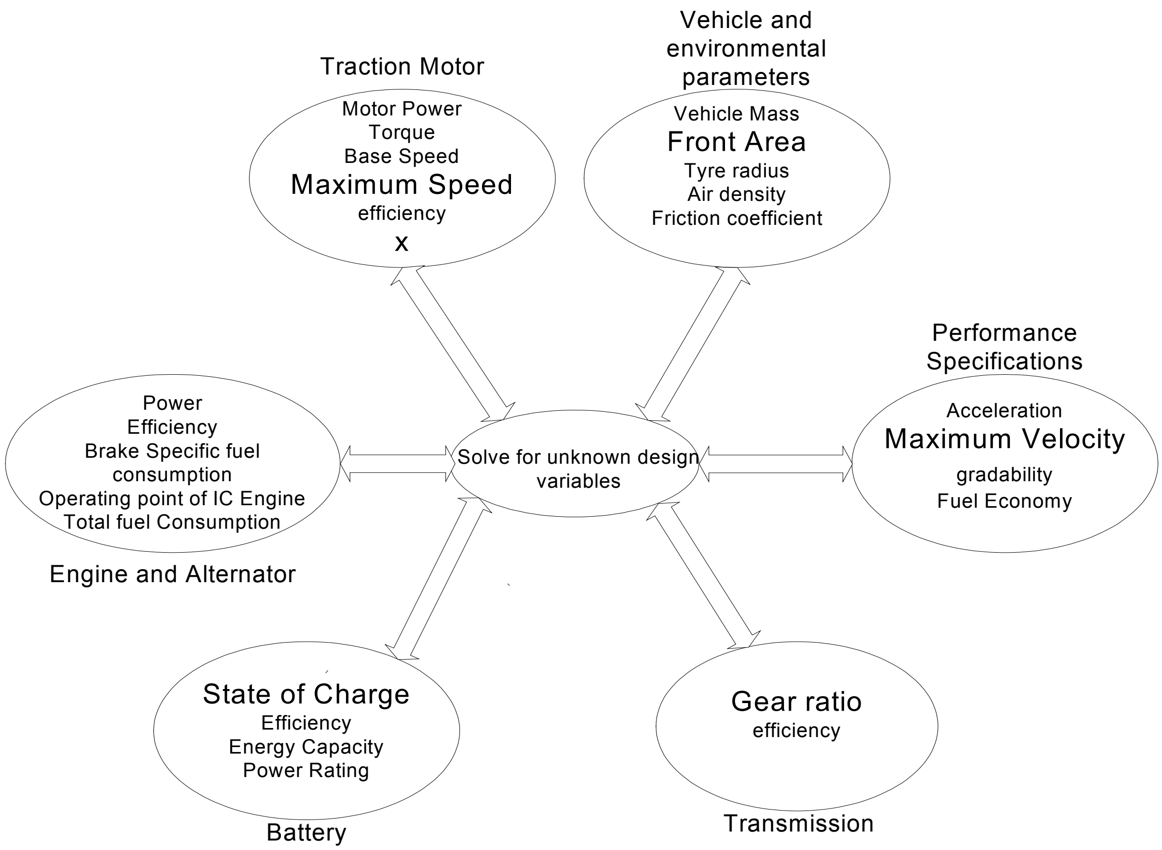


Fig.28. Starting from some variables in some components.

In figure 28, some parameters of each or some of the components are known. These parameters are shown with a larger font. For example, the values of the battery state of charge, the maximum speed of the traction motor, the front area of the vehicle, the maximum vehicle velocity are known to the designer before hand. The unknown values can then be calculated using this new algorithm.

2.Effect of changes in the parameters of one component

In this scenario, the performance specifications are fixed, as in a conventional design. This tool is then useful to study how changes in one component affect the other components, maintaining the same performance specifications. For example, for a given performance specification, the designer wishes to use a motor with half the power rating of the original motor. There might be many reasons for doing so, like limited space available, change in control strategy and so on. With the new algorithm, the designer will immediately come to know the changes that have to be made in the other components, so that the performance specifications are still met with half the motor power.

3.Control degradation scenarios

This is an important asset of this design tool. This tool can be used to analyze the what-happens when type of scenarios. Whenever there are some unwarranted faults in the system, then one or more of the components of that system may malfunction or completely stop functioning. If it were possible to understand the effect of the malfunctioning components on the system, then it would be possible to make changes before hand in the control strategy or the architecture of the system, so that the critical duties can still be carried on even when a fault occurs. For example, knowing the performance parameters that can be achieved with a certain power rating of the motor, the performance parameters with just half the motor power can be observed. The design engineer can then think of ways to achieve the most necessary functions (the car still able to travel albeit at very low speeds) by changing the control strategy.

Another example would be if the battery voltage suddenly drops due to a fault in the battery. The behavior of the vehicle in such a mode could be understood by using a low voltage as an input in the algorithm, and studying the performance characteristics under such circumstances. These failure mode studies help the designer develop as much of a robust system as possible. The tool can be used to study the failure modes by having faulty values as inputs.

4.Optimization for certain design variables

Certain optimizations functions can be included into the design procedure, so that the design procedure can be optimized for a certain performance value like acceleration or mileage. This can be done using all the freedoms given above. Although this feature has not been included in the present algorithm, it could easily be incorporated.

5. Multi- level design

The algorithm can be used for multi –level design of a system. Each component can be treated as a sub-system, which by itself, can be designed using the above algorithm. A sub-system, thus designed, can then be linked to the main system level system. For example, the traction motor, in this system, has only 5 parameters or it contributes only 5-6 design variables to the total number of design variables. This is because the design process is being considered at a very macroscopic level, or the highest possible level for the system. But, the design process of the motor can by itself be very intricate and have a large number of ‘design variables’. So, a traction motor design program using the above algorithm is possible. This traction motor program can then be connected to the main system level design program. Similarly, all the other components can be designed in depth and then linked to the main design program. This would then create a comprehensive package by which a system can be designed at a very microscopic level, using all the advantages listed above.

All the advantages of the new approach that have been listed are possible because the problem of design has been looked upon as a mathematical problem or identifying unknown 'design variables' given the other 'design variables' as inputs. The advantages are a natural outcome of this approach.

Few more functionalities have been added to this algorithm while programming; they are listed below.

6.Verification of the design by simulation

Once the design is complete to the satisfaction of the user, the design can be verified for certain standard drive-cycles. The simulation part of the program gives out the operation pattern of the motor as well as the I.C E over the drive cycle. It shows the instantaneous power delivered by the energy source as well as the peaking power source. The operating point of the engine can be observed and the fuel consumption of the I.C.E in terms of miles per gallon can be calculated. The peaking power source energy level over the entire drive cycle is shown.

All the above plots give the designer a complete picture of the working of the series hybrid electric vehicle, which he has just designed. He can then verify that the engine operates at its optimal region of operation and if the designed parameters along with the decided control strategy are able to successfully meet the drive cycle requirements while maintaining battery state of charge and meet other requirements like acceleration etc. If needed, he can go back and change some of the input parameters till he is satisfied with the results.

7.Specifying the variables over a range

The designer can specify the input design variables over a range, i.e. he can specify a maximum and a minimum for any of the input variables and the output variables are calculated for all the values of this input variable which lie in between the minimum and the maximum. Naturally the output parameters will be observed to be over a range. This ability to input any of the input parameters over a range is of great advantage as he can then observe the trend in the output parameters as the inputs vary over the range. It gives him an understanding of the nature of relation between certain input and output variables. For example, if the design variable 'x' (defined earlier) is varied from say 2 to5, it can be seen that traction motor power rating decreases with an increase in the value of 'x'. Such trends are thus useful when design is done over multiple iterations; if the need is to decrease the power rating of the motor, then chose a higher value of 'x'. The designer can converge to his optimal (desired) design much faster if he understands the trends between variables and gives his inputs keeping those in mind.

8. Plotting the design variables as a design space

The input as well as the output design variables can be plotted in the form of single dimensional (line plots on a number line) as well as two or three-dimensional plots of one design variable against another and so on. If the input variables are over a certain range, then the plots will show what can be called as 'design spaces'. This design space will encompass all the possible design points for the range of the input variables. Again, as the user gives different inputs for different iterations, the design space will shift, contract or even expand. The designer can go on performing iterations of a design till he arrives at a particular point in the design space, which is highly optimal for him.

9.Point in range out scenarios

As explained earlier, there are certain scenarios possible where in the physics of the system induces certain scenarios into the system. It should be noted that these scenarios might be such that they are not present in every design iteration, but these scenarios do turn up for certain types of inputs and certain types of outputs. Hence these scenarios cannot be written in the design rules as equations, but are to be considered only when the conditions arise. Such scenarios lend themselves to possibilities wherein for given point inputs, outputs over a range are possible. This is extremely useful to a designer as he gets the freedom to move over the entire range for that particular variable, for the same point inputs that he has provided. He can then proceed for further iterations by selecting points of interest in the range available to him. The table below lists the 8 freedoms and their possible applications in a design process

D. Realization of the new approach

In Section B, the new approach towards design was introduced. Section C listed the numerous freedoms that were possible due to the new approach and how these freedoms could be exploited for a better design. This section explains how the new design tool has been realized, specifying the algorithm used for design. As stated earlier, this algorithm looks at the design problem mathematically. The freedoms and the applications are mentioned in Table 2.

Table 2: Freedoms of the new design tool and possible applications

No	FREEDOM	APPLICATION
1	Start design from any Component	1.Study effect of that component on performance; 2. Effect on other components for given performance
2.	Start design by specifying certain parameters of some/all components	1.Possible to design a drive train for fixed values of certain parameters. 2. Enter 'degraded' values of some parameters (example – D.C. bus voltage) to emulate malfunctioning component and study its effect on the system. This can be sued to study control degradation scenarios.
3.	Include Optimization algorithms	Optimize drive train for mileage, power, compactness etc.
4.	Multi-level design	Detailed design from component level to system level, enjoying all the freedoms stated above.
5.	Input variables specified over a range (minimum-maximum)	1. Observe effect of change in the parameter on the performance or other components as a trend. 2. Helps to understand the nature of relationship between one variable and the other.
6.	Simulation (freedom by programming)	Verify the design for constraints,
7.	Plotting of design variables in one, two and three dimensional space	1.Observe changes in design space as parameters vary, 1. Observe changes in design space as parameters vary 2.Perform multiple iterations to shrink the design space to a point
8.	Point input – range output scenarios.	If the user has under specified the system, the algorithm injects values for one or more design variables over a very wide range so as to give ranges in the output.

The equations, which involve these design variables and are used to design the power train, have been stated in Chapters II and III. The equations are listed below.

1 $P_m = \frac{M_v}{2t_a}\left(V_f^2 + V_b^2\right) + \frac{2}{3} M_v\, g\, f_r\, V_f + \frac{1}{5} \rho_a\, C_D\, A_f\, V_f^3 (W)$

2. $P_{e/g} = \frac{V}{1000\, \eta_t\, \eta_m}\left(M_v\, g\, f_r + \frac{1}{2} \rho_a\, C_D\, A_f\, V^2\right) \quad (kW)$

3. $P_b \geq \frac{P_{m,\max}}{\eta_m} - P_{e/g}$

4. $E_{cap} = \frac{\Delta E_{\max}}{SOC_{top} - SOC_{bott}}$

5. $i_g = \frac{\pi\ n_{m,\max}\ r}{30\, V_{\max}}$

6. $Ft = M_v\, g\, f_r + \frac{1}{2} \rho_a\, C_D\, A_f\, V^2 + M_v\, g\ i$

7. $Ft = \frac{\eta Pm}{V}$

8. $Tm = \frac{Pm \times 60}{n_{m,\max} \times 6.28}$

9. $x = \frac{n_{m,\max}}{n_{m,base}}$

Where,

P_m = Traction motor power in Watts

M_v = Mass of the vehicle in Kg.

t_a = Time required for acceleration from 0 to velocity V_f (m) in seconds.

V_f = Final velocity to measure acceleration performance.

V_b = Velocity of the vehicle corresponding to the base speed of the motor in meters.

f_r = Coefficient of rolling resistance at the tires.

ρ_a = Air density in kg per cubic meters.

C_D = Coefficient of aerodynamic drag.

A_f = Front area of the vehicle in square meters.

$P_{e/g}$ = Engine/generator power rating.

η_t = Transmission efficiency.

η_m = Efficiency of the traction motor.

P_b = Battery power in watts.

E_{cap} = Energy rating of the battery in KWH.

$\Delta E_{\max}$ = Maximum variation in energy of the battery over a complete drive cycle.

SOC_{top} = Maximum state of charge of the battery allowed by the controller.

SOC_{bott} = Minimum state of charge of the battery allowed by the controller.

i_g = Value of the gear ratio between the wheels and the traction motor.

$n_{m,\max}$ = Maximum speed of the motor in R.P.M.

r = Radius of the wheel in meters.

$V_{\max}$ = Maximum vehicle velocity in meters per second.

$n_{m,base}$ = Base speed of the motor in R.P.M.

Ft = Tractive effort in Newtons.

$i = \sin\alpha$, Where α is the gradient angle.

Tm = Motor torque in Newton –meters.

x = Speed extension ratio for a given motor.

There are 9 equations and 26 variables used in the algorithm. Note that not all the design variables are meant to be input/output variables; in order to simplify the problem of solving the simultaneous equations, some of the variables will be regarded as constants in solving the equations. All the variables pertaining to the efficiencies will be constant values. The above assumption is reasonable in the sense that motor efficiency does not vary much (not more than 5%) over its entire speed –torque curve. Similarly, the control strategy maintains the operating point of the engine at its optimal position, thus maintaining constant efficiency throughout. The S.O.C of the battery is maintained over a very close variation (for example 0.4 to 0.6) thus ensuring that the efficiency is nearly constant. The values of the 'constants' will always be provided by the user, they are not considered as design variables but can be though of as 'parameters' of the system.

There are three scenarios in which the above freedoms and applications can be categorized. They are

1. Point values in – Point values out.
2. Ranges of values in – Ranges of values out.
3. Point values in – ranges of values out.

Before understanding the algorithm of the tool, it is essential to understand the following points.

1. All the equations, which have been stated above are algebraic polynomial equations.
2. The variables take only positive, non-zero real values.

3. Since these equations are polynomial equations, each variable can be expressed as a continuous function of he other variables.
4. There are two equations in which there are terms of the second order and third order, namely the velocity terms. But, since we are dealing with physical terms only positive values for the velocities will be considered. Therefore, there is a unique positive value for velocity for each power etc.

It is pretty obvious that simply solving the equations simultaneously, we cannot have range outputs for point inputs. So, another approach was chosen. After looking at the equations, the following things can be observed:

1.Mass and motor power (Pm) are the only two variables that are common to more than two equations out of the set of nine.

2. If different set of equations calculates different values of motor power Pm, then a range output for Pm ranging from the minimum value to the maximum might be possible. The same holds true for mass. Knowing this, we can split the equations in to boxes as shown in figure 29. The only variables that are common to between the boxes are the variables mass and motor power.

The following strategy is now used which can be applied to: The equations are split into 4 boxes, so that the only common parameters between the boxes are mass and power. We will discuss situations for only one variable, and that is power. The same logic can be applied to mass.

For power, two scenarios arise:

1. Power is given: Each block used the given power to solve the equations within simultaneously.

2. Power is not given: Again two scenarios arise

a) Only one block is capable of calculating power: The other blocks use this value of power for solving the equations in their own block.

b) Two blocks or more blocks produce power: Then, a range is possible depending on the given scenarios. The motor power range logic block generates a range. It sends the power range back to the to the individual blocks which solve for the unknowns again so that all the parameters which depend on power and which have not been specified have a range at the output.

The exact same logic is applied to mass.

1. Mass is given: Each block used the given mass to solve the equations within simultaneously.

2. Mass is not given: Again two scenarios arise

a) Only one block is capable of calculating mass: The other blocks use this value of mass for solving the equations in their own block.

b) Two blocks or more blocks produce mass: Then, a range is possible depending on the given scenarios.

For the given system, only these two scenarios can be envisioned. But, as the system gets complex, there will be many more variables and the logic will get more and more complicated. It might happen that the 'box' logic used for this system will have to be changed to another logic. But, if the designer is able to make out the connection between the variables by experience or observation, then such logic is possible. Generally, systems with various components connected together have nodal variables which can be used over a range.

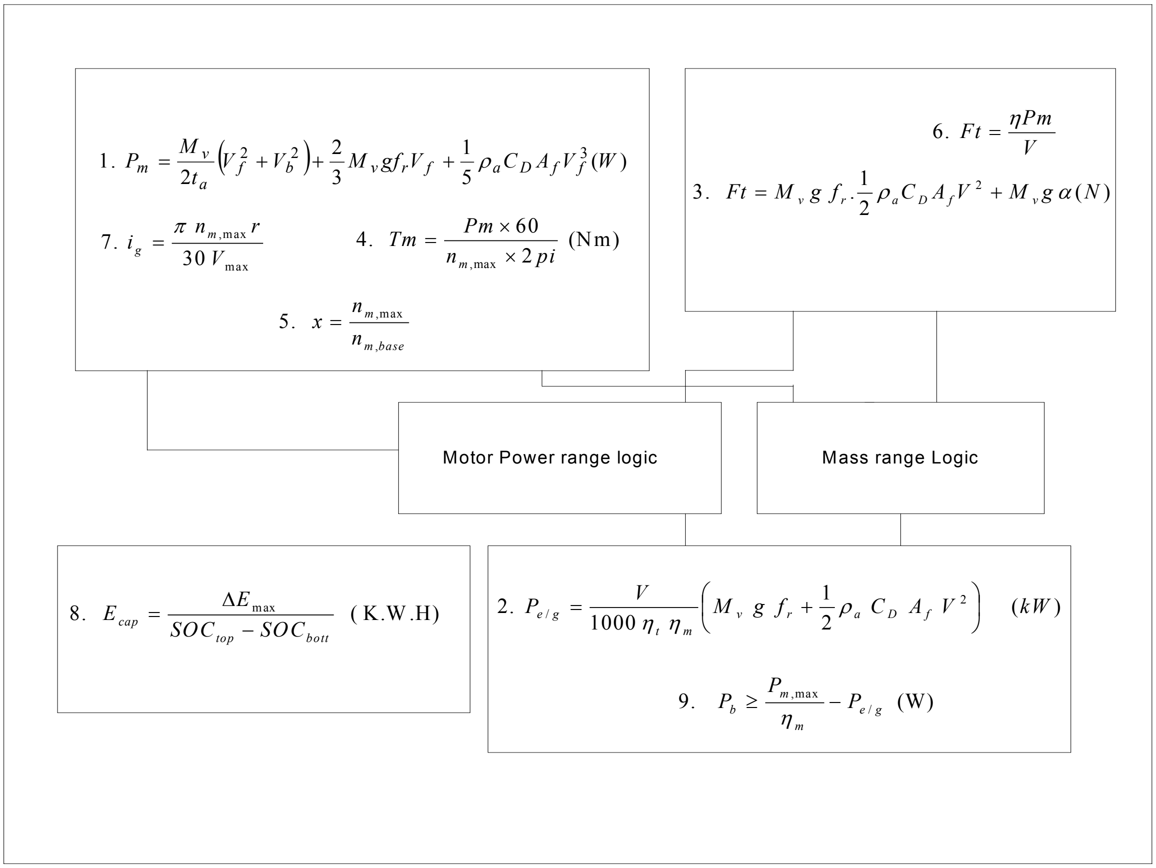


Fig.29. Boxes for the set of equations considered.

E. Limitations of the new tool

For the range in range out scenario, the algorithm calculates the values for the output variables for the combinations of the minimum and the maximum values of the input variables; the values for the output variables for the values of the input variables in between the minimum and the maximum are not calculated.

Since the equations, which are used in the design, are polynomial equations with all the variables taking positive real values, as stated above, any of the variable can be expressed as a continuous function of the other variables [13]. Hence, the value of any output variable, which is the function of the input variable whose value is in between the maximum and the minimum of that input variable, will always lie within the boundaries set by the maximum and minimum of the output variable.

The above statement is a given for continuous functions, but van be proved using theory of multivariable calculus [14].

So, if the equations were not polynomial and continuous as in this case, then value of the output variables for each of the input variables would have to be calculated. The design space will then be non-continuous.

Although the code has been written only for continuous design spaces, the basic concept of splitting the equations into smaller subsets is still applicable to dis-continuous solutions spaces, after making adjustments to the code.

F. Summary

The concept of the omni –directional design tool has been introduced. The freedoms provided by the new tool have been summarized. The chapter also gives an outline of the algorithm of the new tool.

CHAPTER V

OMNI – DIRECTIONAL DESIGN TOOL

A. Introduction

The last chapter introduced the concept of omni directional design tool. The chapter also highlighted various freedoms associated with the new approach and the applications of the various freedoms. In this chapter, the actual software tool will be discussed. Numerous design examples will be shown in order to show the flexibility of the tool and support the claims made in the earlier chapter.

B. The user interface

The tool has five GUIs (Graphic User Interface). The first GUI can be used to access the other GUIs. Each GUI will be explained in detail on the following pages.

1.The first page

On the computer screen, the first page looks as shown in figure 30 below. Each button on the front page links to another GUI. This page can hence be used to navigate to other pages as required by the user. When the 'HELP' button is clicked, a word document containing text on how to operate the GUIs comes up.

The first page comes up when the v_mutant.m file is executed. It should be mentioned that the programming of this software, including the graphic user interface (GUI), has been done in Matlab for simplicity in programming. It can be done using any programming language as per the designer's convenience.

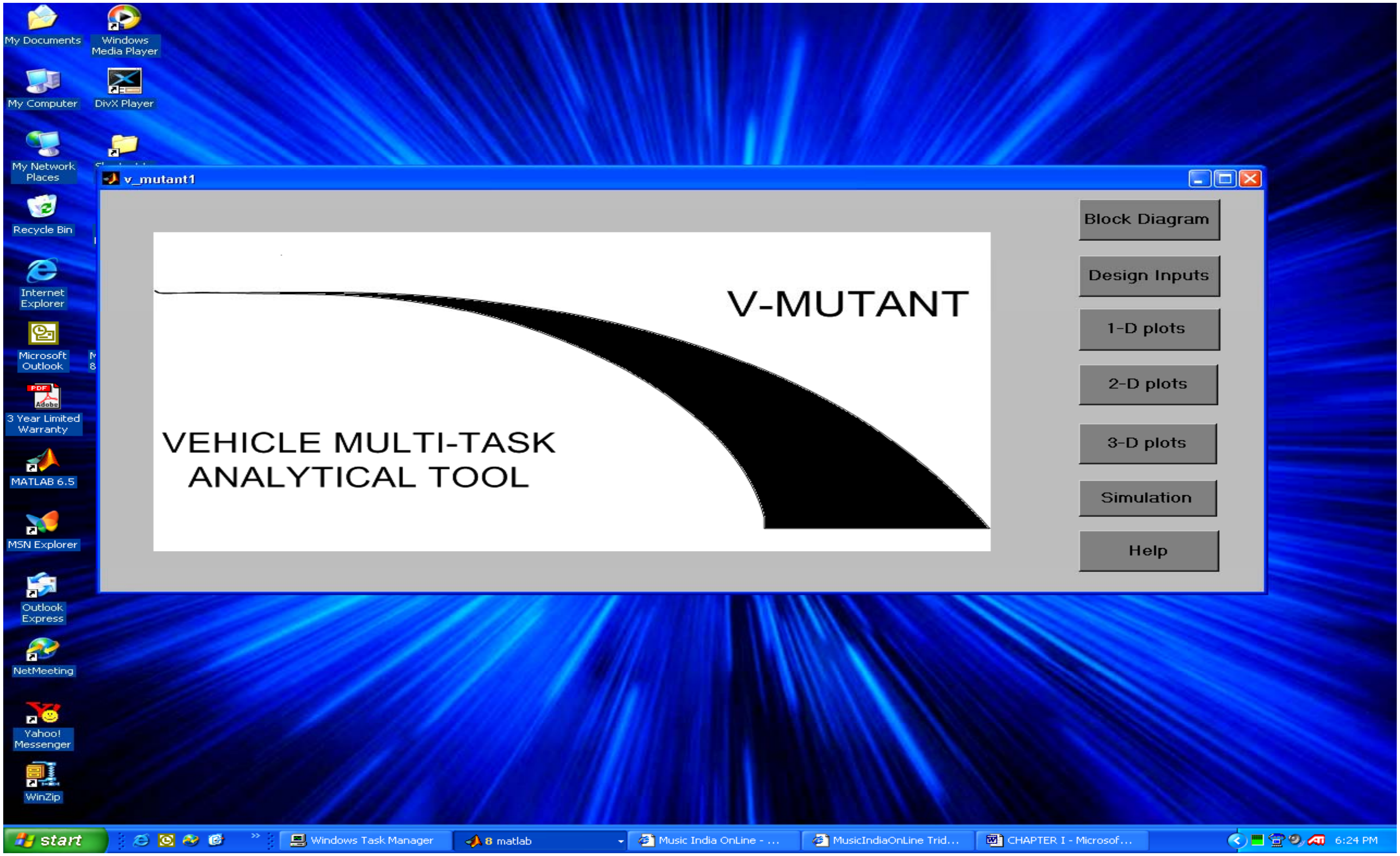


Fig.30.Screen shot of the first page.

2.Block diagram

When the button labeled block diagram is clicked, a block diagram of the series hybrid comes up. This figure (figure 31) indicates the parameters of each component available for design. It should be noted that not all the components can be used as design parameters, but the values of some of the components have to be provided for the design to be possible. As has been explained earlier, this is done because all of those design variables do not influence the design process much and are not central to the components.

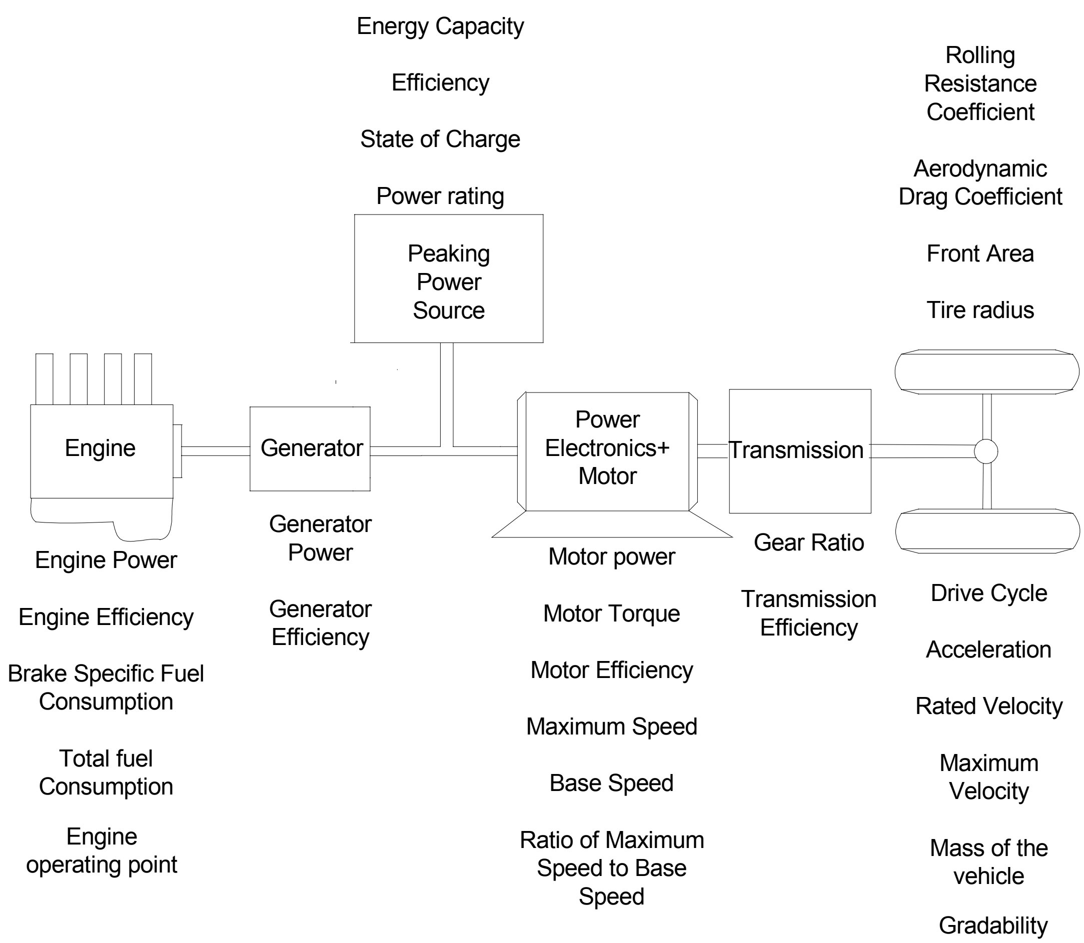


Fig.31. Block diagram indicating the components available for design.

It can be seen that this figure is exactly the same as figure 21. This insertion of this figure is necessary and important. It gives the user the list of variables that are used in the program. In a way, this figure defines the depth of the design process, and the user immediately comes to know if the design is on a system level or on component level or on a composite level. This figure also shows the architecture of the hybrid considered; as discussed in chapter I, the hybrid can have more than a single architecture. The performance of the vehicle varies with different architectures; it is very important that the designer knows the architecture that is being used in the design. Although for a series hybrid this architecture is nearly always fixed and is as shown in figure 31 above, a similar omni-directional design process for a parallel hybrid would be possible for any of the many architectures of a parallel hybrid, and hence the knowledge of the architecture assumes importance.

This also underlines a drawback with this design tool. The design tool assumes that the designer has already chosen or fixed the architecture before he starts with the design process sing this design tool. Thus, this design tool does not allow the designer the freedom to choose different architectures.

3.Design inputs GUI

This is the main page of the design tool. As the name suggests, the designer, after deciding the inputs design variables from the block diagram, enters the values to the variables on this page (figure 32).

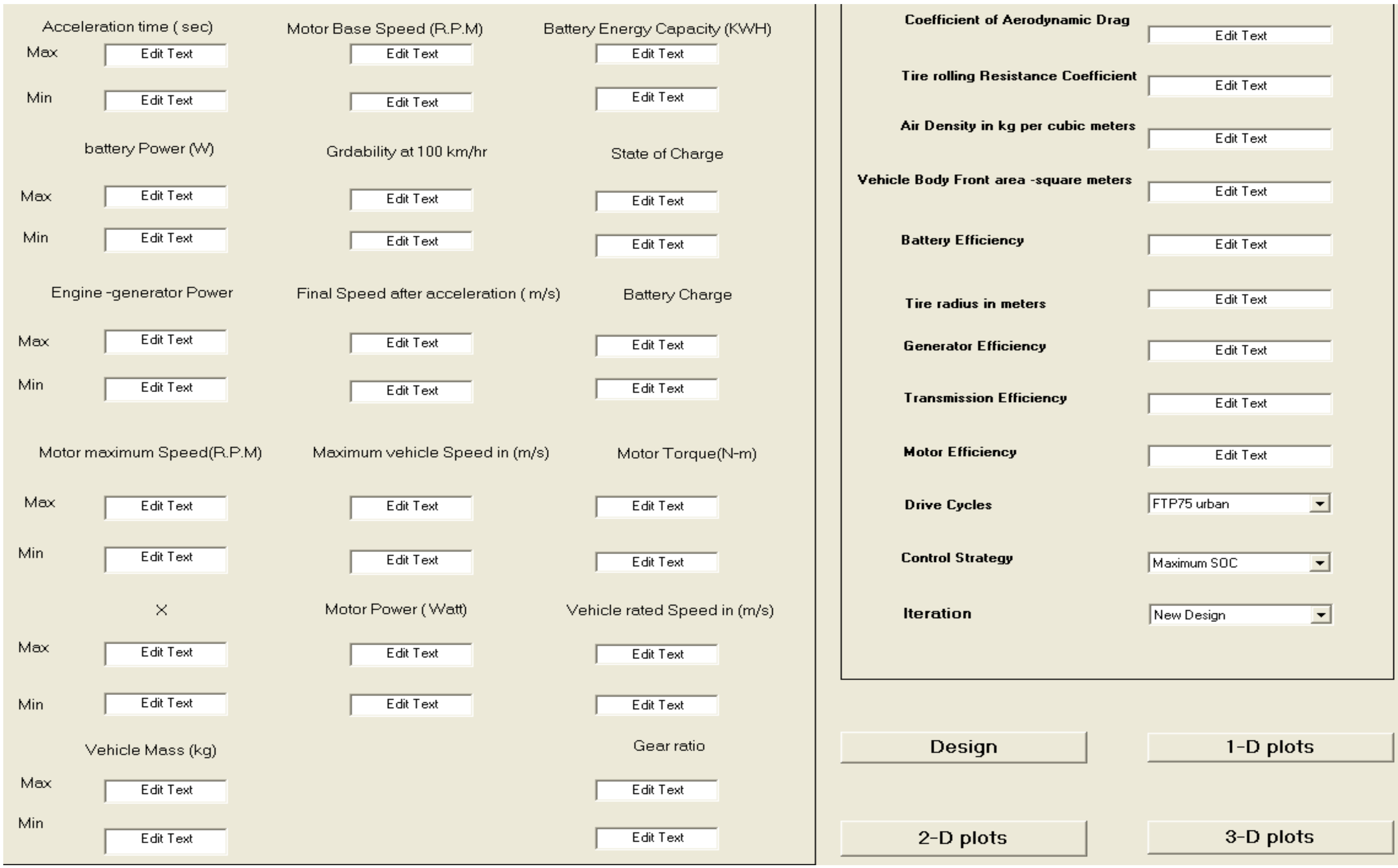


Fig.32. The design input GUI

The above figure shows how the GUI looks when opened. All the 'text' spaces listed under each of the design variables have ' Edit Text' written in them, which means that they are essentially empty and the variables have not been assigned any value. It can be seen that there are two sections. In one section, the variable names have been written with a dark font. Also, just these variables can take just one value, unlike the variables in the other section, where the variables can take values within a range (max and min). The variables to the right in the dark font are the variables that have to be specified for each design. Unless values are assigned to these variables, a design is not possible. These variables are not the 'design variables' but can be referred to as parameters of the system. As explained in the earlier chapter, these variables are efficiencies and environmental variables like air density, friction and air drag coefficients etc and can be considered constant. A drive cycle as well as a control strategy is necessary to simulate the vehicle designed using this algorithm. Both can be chosen from the corresponding drop boxes. As this design process can go on over iterations, specifying the number of iterations is needed.

The inputs in the left section are the 'design variables'; they can be either inputs or outputs as decided by the designer. As this tool provides the designer with the facility to input certain variables over a range (e.g. the mass of the vehicle can vary over a range from 1000 to 1500 RPM). In that case 1500 will be entered in the upper box under the 'Vehicle mass in kg' title, and 1000 in the lower. If the mass is a point input, then the same value will be entered in both the boxes.

Once the designer has entered the input design variables, he presses the 'design' button. Any variables for which values have not been entered are considered as output variables. The program then calculates the values for the unknown variables. After the design is complete, the boxes that were empty (for which no values had been entered) now have the calculated values. Figure 33 shows an example of the GUI with the input variables. The calculated values can be a single point value or the values can be over a range. If the calculated value is a point value, then both the maximum as well as the minimum fields will hold the same number. For example, the design variable ‘ x’ in figure 34 is an output variable, and has a point value. Hence the maximum as well as the minimum fields of that variable will have the same value. If the output varies over a range, then the maximum of that range will be in the max field and the minimum will be in the min field.

A GUI after the deign process is complete has been shown (figure 34). After the design is compete, the variables can be plotted as single dimensional plots. The variables can be plotted against each other as two or three-dimensional plots. These will be explained more along with the design examples.

After observing figure 34, one can infer the following

1. The design process was a point design, in which the input variables were defined as point or single values (with the exception of state of charge, which necessarily varies over a drive cycle, and the parameter considered for calculation is the change in state of charge) and the output or unknown variables turned out to be point values.
2. This was the first iteration of the design.

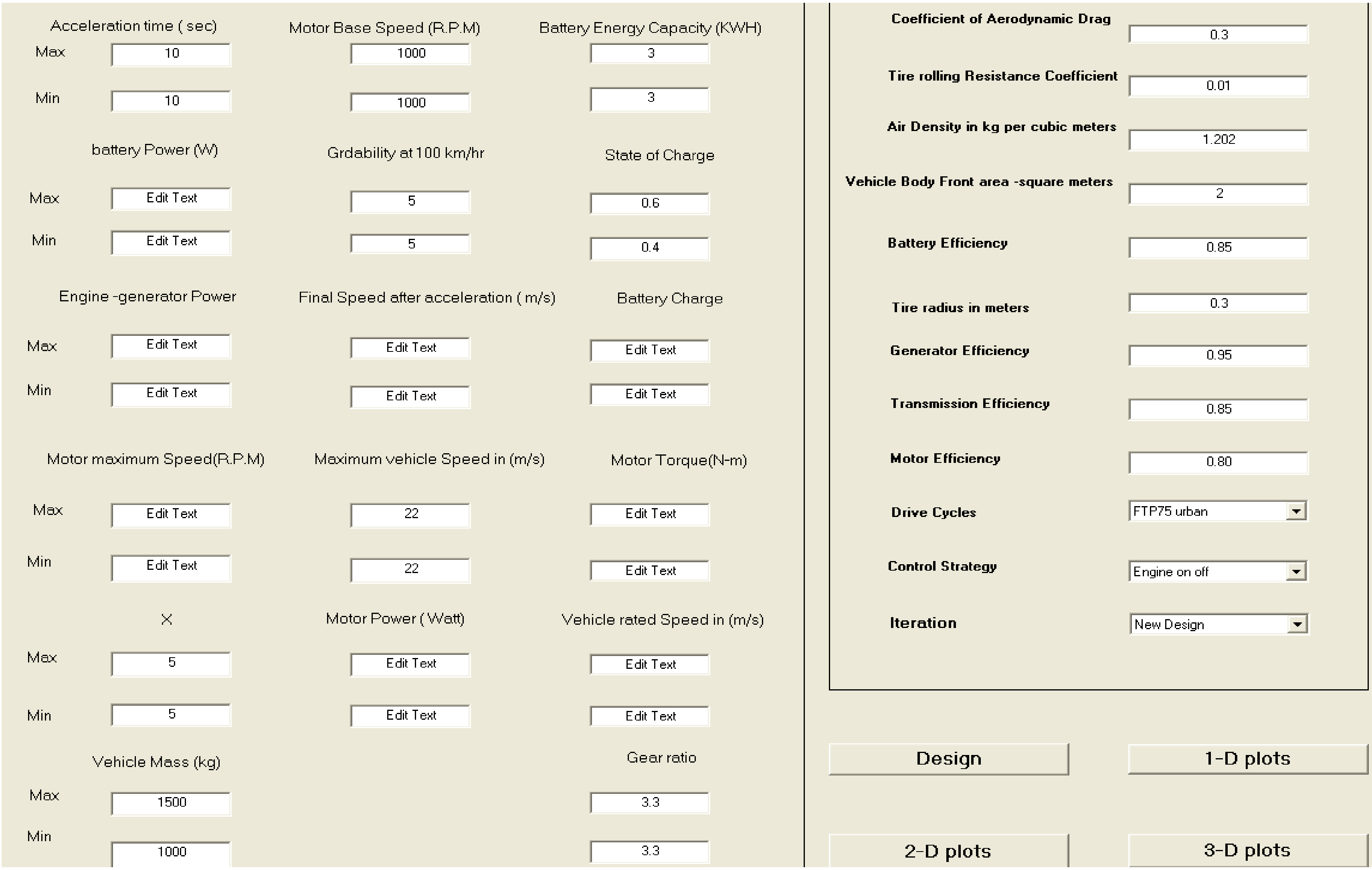


Fig.33. Design GUI with values entered for some inputs.

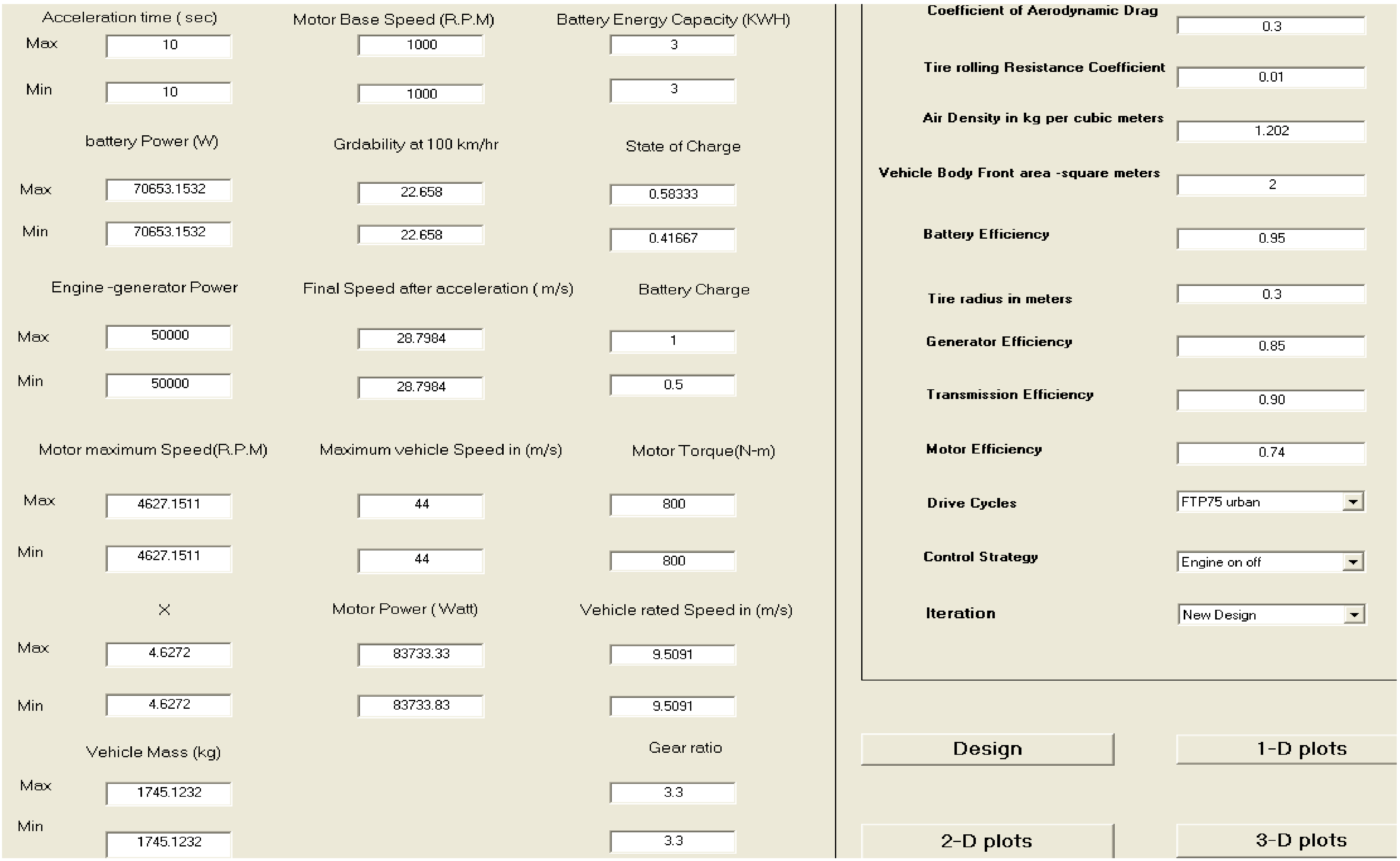


Fig.34. A completed design.

C. Design examples

The eight freedoms explained in the previous chapter can be classified into three categories depending on whether the inputs as well as the outputs are over a range or are point values.

1. Point input point output scenarios.

2.Point input range output scenarios.

3.Range input range output scenarios.

The following sections will have three design examples, for each of the above scenarios.

1.Single input single output scenario

In this scenario, the designer arbitrarily chooses some design variables as input variables and assigns values to them. This would not have been possible in the case of a conventional design, because he would have been forced to assign performance variables as his input variables. Following is the statement of the problem:Design a series HEV power train given the following parameters:

1. Gear ratio = 3.3,
2. Motor torque = 800 Nm,
3. Battery energy capacity = 3 KWH.
4. Time to check acceleration performance = 10 seconds.
5. Engine /generator power = 50 KW,
6. Maximum vehicle velocity = 44 meters per second,
7. Motor base speed = 1000 R.P.M.

8. Variation in battery charge over a drive = 1 to 0.5.

Use the hysteresis control strategy.

In figure 35, the input components have been shown in a larger, bold font with italics. It can be clearly seen that the input design variables are from various components and not from the performance specifications alone.

The values of the variables are entered into the design input GUI similar to figure 34 above. After pressing the design button, a completed design is obtained with values of the unknowns similar to figure 35.

The values obtained for the unknowns are as follows:

1. Battery power = 70653.1532 W.
2. Motor maximum speed = 4627.1511 R.P.M.
3. Gradability = 22.658%.
4. Final speed after acceleration = 22.658 meters per second.
5. Motor power = 83733.3333 W.
6. Variation in state of charge = 0.58333 – 0.41667.
7. Miles per gallon = 40.5447.

After the values have been obtained, the design parameters can now be used to simulate the performance of the designed vehicle over a drive train (Figure 36). The miles per gallon value is also calculated for the given drive cycle.

The design was started from arbitrary variables; hence there is no guarantee that the completed design will make practical sense in terms of the sizes of the motor or battery obtained. The simulation helps to verify that the calculated as well as the given variables put together can actually form a hybrid vehicle.

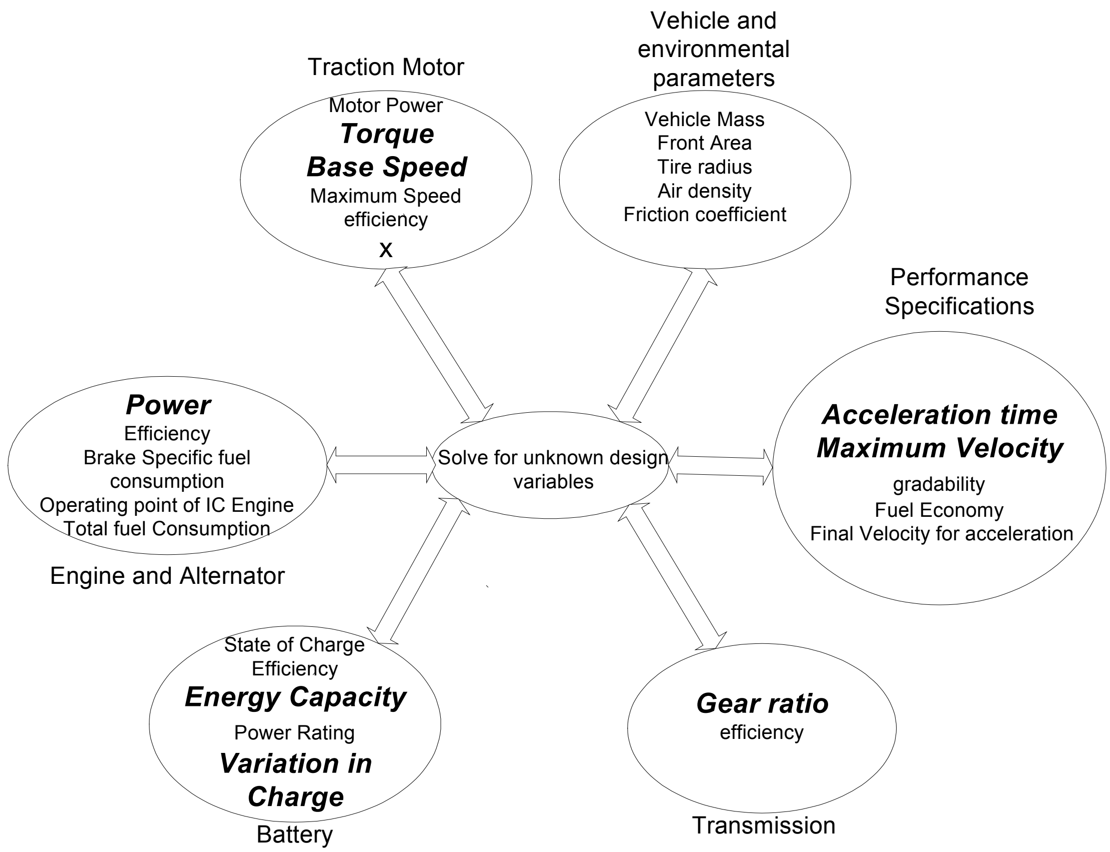


Fig.35. Input variables for the point input – point output scenario.

It once again needs to be emphasized that theoretically, all of the 29 variables mentioned in the 9 equations of the earlier chapter can be design variables. But for simplicity, only those variables that affect the design in a dominating way, have been considered in the above process. So, for figure 35 above, engine efficiency or battery efficiency cannot be considered as a design variable as far as this dissertation is concerned. But we see that in principle, it is possible to have any of the efficiencies and other variables as design variables.

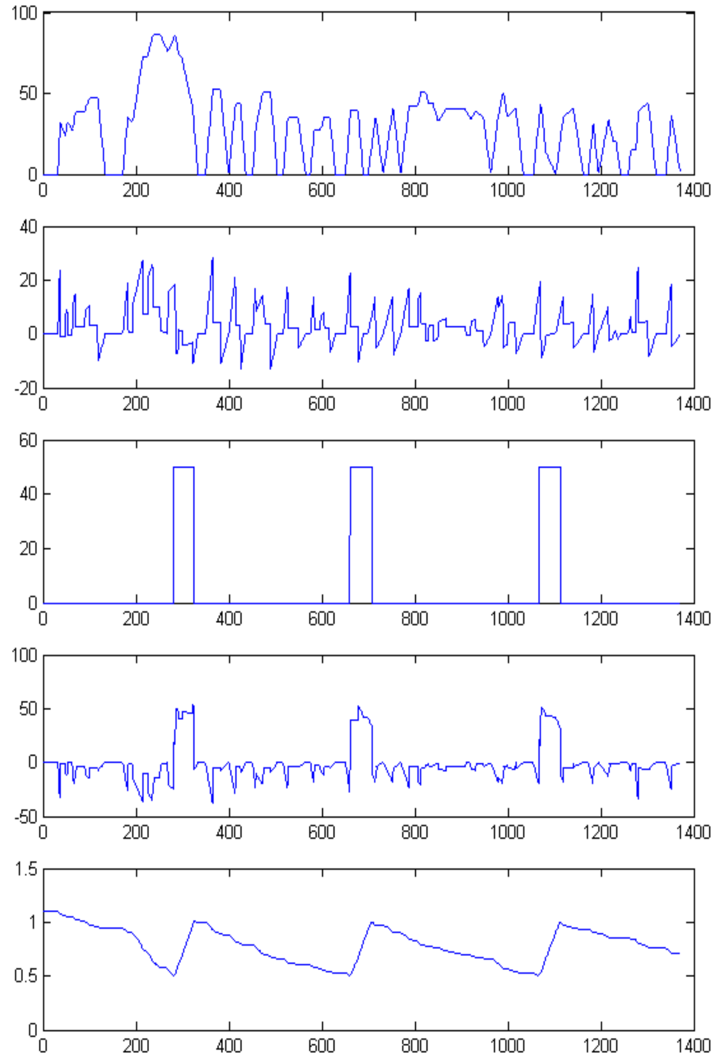


Fig.36. a) Drive cycle b) motor power versus time c) engine power versus time d) battery power versus time e) battery energy level versus time.

After the design is complete, the vehicle is simulated for its performance over a drive train. The results of the simulation are as shown in the figure 36. One can easily see the engine turning on and off as the SOC varies between 1 and 0.5. The battery power is positive when the engine is on, which means that the battery is getting charged.

2.Range input - range output scenario

In this scenario, the designer specifies one of the input design variables over a range. He then modifies the range over the future iterations till he converges to a point of his own preference.

A designer has been provided with the following specifications:

1. Mass of the Vehicle = 1500 kg.
2. The Motor torque should be 600 Nm.
3. The maximum velocity for acceleration performance = 22 meters per second.
4. The maximum Motor Speed is 5000 R.P.M
5. The Time for acceleration test is 10 seconds.
6. There are different types of motors, with the 'x' factor varying from 2 to 5.
7. Gradability at 100 kmph should be greater than 5%.
8. Battery energy capacity is 3K.W.H
9. The Battery state of charge varies from 0.6 to 0.4.

The designer has to finally arrive at a single value of 'x' for the vehicle. The designer enters the known design variables along with the other peripherals like efficiencies, etc. He gets results on the design page. He plots results as two-dimensional plots with one variable against each other (Figure 37). The 2-D plots GUI can be directly accessed from the Design page by pressing the corresponding button. Here, there are 9 two-dimensional plots available to the designer. He can select any of the variables (Input or output) of his choice on the X- axis as well as on the Y-axis. These variables will then be plotted against each other for the current as well as the previous iterations. The plot can be a design space if the variables are over a range, or can be a point. As the designer is able to see the plots for the previous iteration too, he is able to observe the changes in the values of the variables from one iteration to another, and understand the trends. Of particular interest to him is the plot of motor power versus ‘x’. (Plot #1).

One of the major advantages of the multiple two-dimensional plots available to the designer is the ability to observe the behavior of several variables at a time, and that too for all the iterations. This gives the designer a lot of insight into the design process, as he is able to correlate the behavior of various design variables at the same time, and understand the effect of changes in one variable on many other variables at the same time. It requires a lot of experience and expertise to imagine such scenarios.

This is especially the case if the system is complex and the designer has many variables to consider, while for a simple system, tool is redundant.

Although the tool does provide a visual aid that is otherwise difficult to imagine mentally, the conclusions drawn totally depend on the skills of the designer.

As a second iteration, the user restricts the range of ‘x’ from 4 to 5. He keeps the other inputs the same. He again plots the variables against each other in the form of two-dimensional plots, super imposing on the fist iteration plots. He observes that as he is increasing the value of ‘x’ the value of motor power is decreasing, in spite of other inputs being the same. Similar observations can be made for the other plots, which he plots with the other two-dimensional plots available to him.

The behavior of the various variables also tells him the relationship that exists between various variables that are not plotted against each other. If the design space is a single point, then a ‘*’ is observed, as will be seen in the later figures.

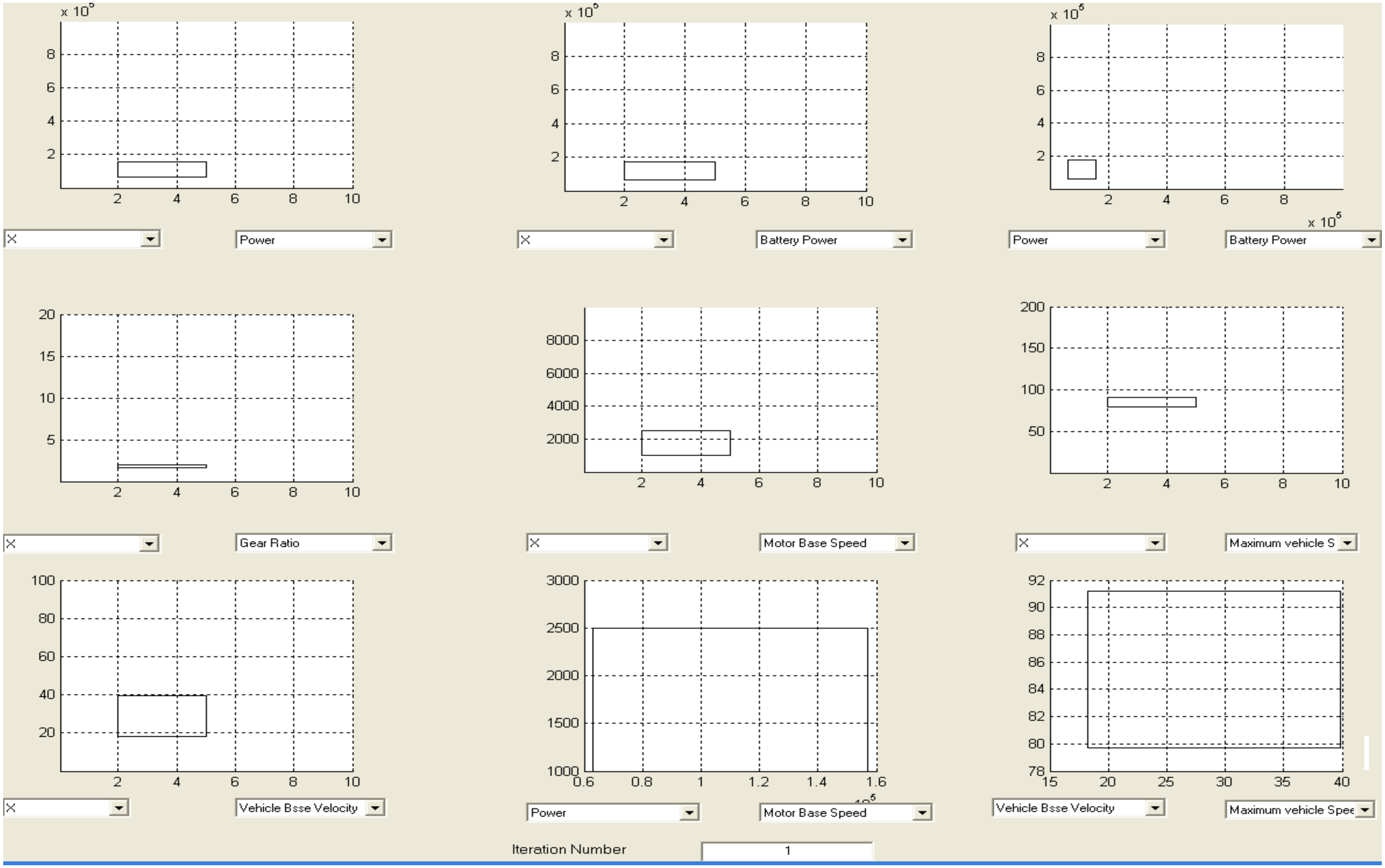


Fig.37. Two dimensional plots for the first iteration.

He thus concludes, that choosing a higher value of ‘x’ will let him have a motor with a smaller power rating, for the same performance. As the motor size is decreasing, the battery size is going to reduce as well, since the battery, along with the generator, supplies power to the motor.

Having concluded thus, the designer then selects a value of ‘x’ =5 for the third and final iteration. He observes that for x=5, he gets maximum power keeping the inputs the same. (The red ‘*’ in Figure 38 is the final iteration; the larger boxes are the first iteration and the smaller boxes refer to the second iteration).

Some other trends to be observes are that battery power decreases with an increase in ‘x’ (Plot #2). The gear ratio, motor base speed, Vehicle base speed also decrease with an increase in ‘x’. (Plots 4,5,7). The plots have been counted from the left upper corner in a horizontal fashion. The Designer can also plot the various plots in the form of a single dimensional plots; i.e. each variable is simply plotted on a number line. It is very easy to see the changes in the range of each variable for each iteration on a single line plot (Figure 39). The red bar is the range for the first iteration, the blue bar for the second and the green for the third. For variables with a constant value, a single ‘*’ of the color corresponding to each iteration is seen.

Although the above single line diagram (figure 39) shows just a few of the total design variables, the designer can actually plot all the variables as shown above. A three dimensional plot is also possible for any of the three variables (Figure 40). One can see in the three dimensional plot that as the range of ‘x’ becomes smaller, the design space shrinks. The blue dot at the corner is the final design after the third iteration.

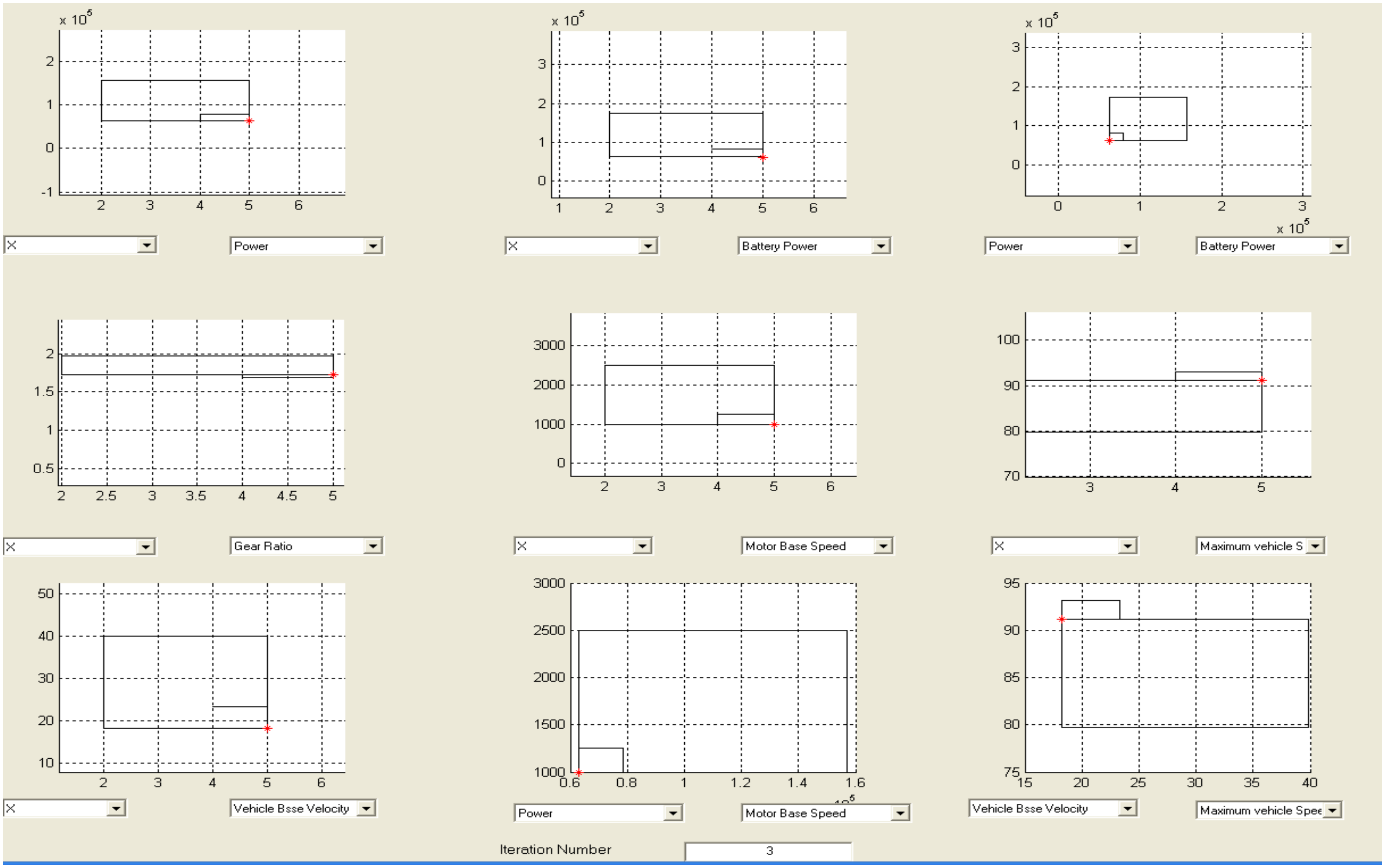


Fig.38. Two dimensional plots for the final iteration.

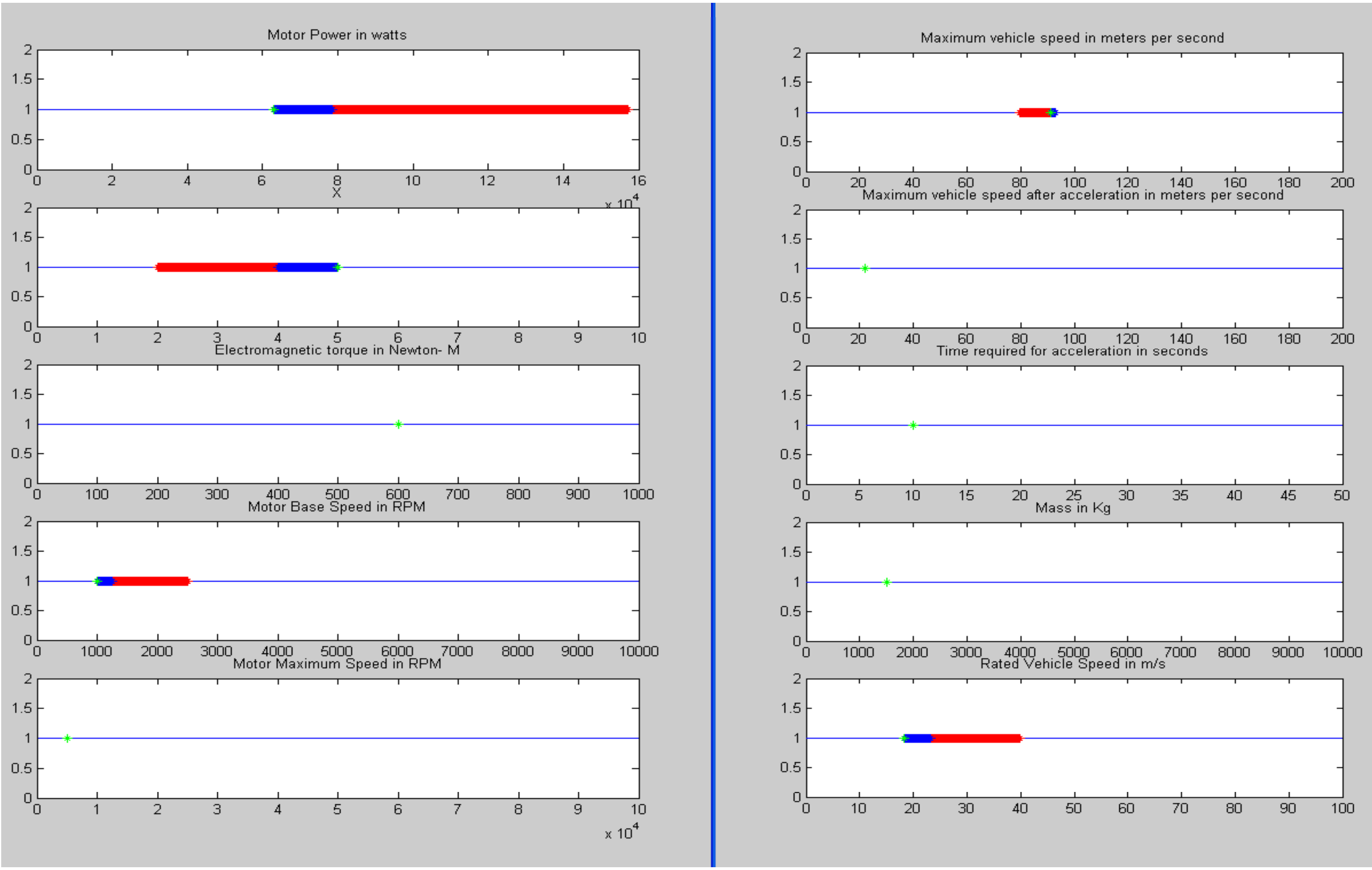


Fig.39. One dimensional plots for range input range output scenario

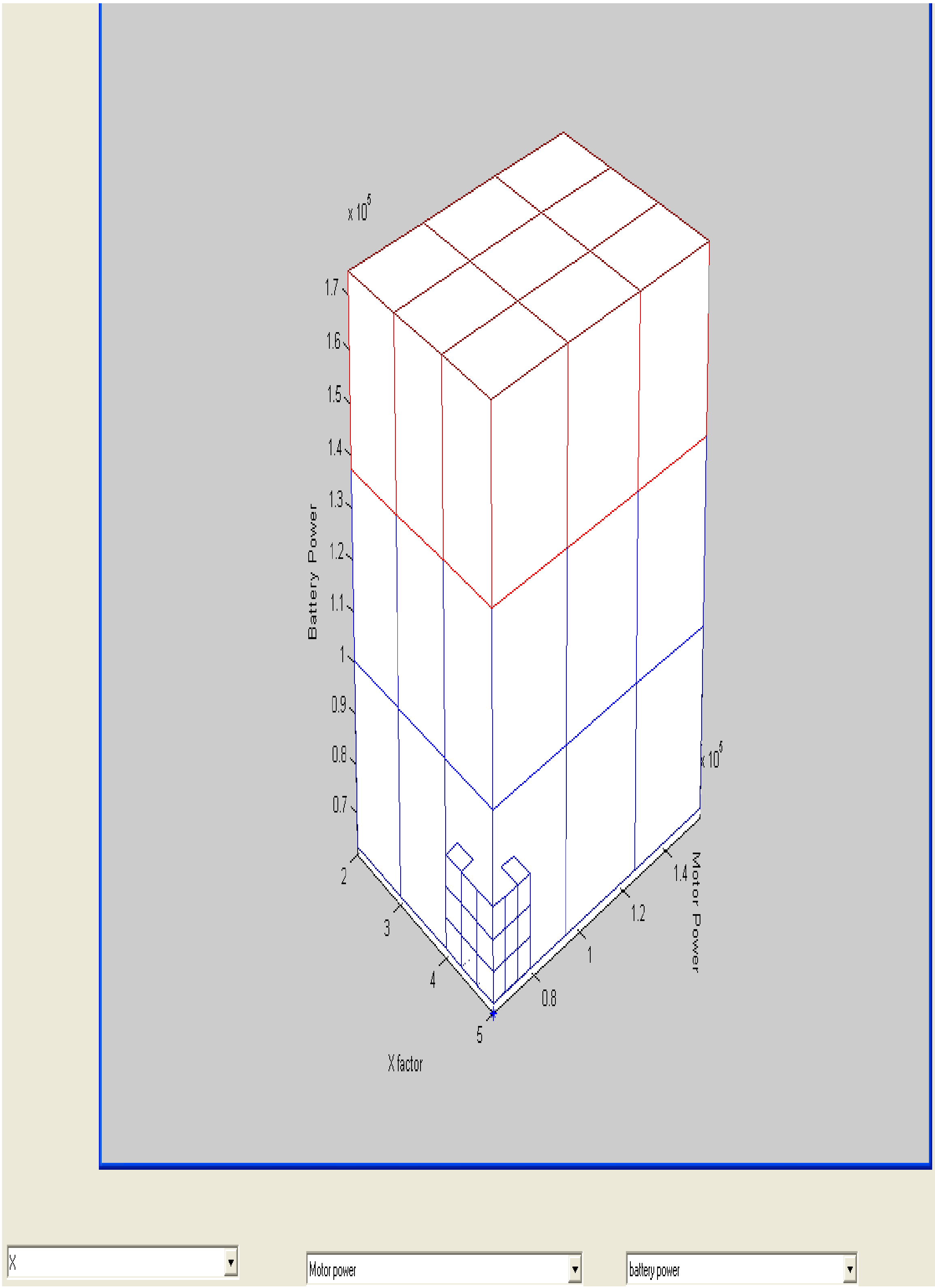


Fig.40.Three dimensional plot of the range input range output scenario.

3.Point input – range output scenario

As discussed in the previous chapter, this scenario occurs when the physics of the system applies some restrictions or boundaries on the design space of certain variables. Consider the following problem:

Design a series HEV using the Omni – directional design tool with the following design variables already being specified:

1. Acceleration time = 10 seconds.
2. Battery Capacity = 3 K.W.H.
3. Final Speed for acceleration = 22 m/s.
4. ‘x’ factor =5;
5. Vehicle Mass = 1500 kg.
6. Gear ratio = 6.6.
7. Vehicle Rated Speed = 10 meters per second.
8. Battery Power = 70000 W.
9. Engine generator Power = 20000 W.

Note that al the inputs are point inputs. We see that in spite of the inputs being point inputs, some outputs are in the form of ranges.

The values of the various output variables is given below:

1. Motor Maximum Speed (R.P.M) is 10516 – point value.
2. Maximum vehicle speed in m/s id 50-point value.
3. Motor base speed is (RPM) is 2100.3 – constant point output
4. Gradability at 100 kmph varies over a range from 13.14 t o 6.5 – output over a range.

5. Motor Power also varies from 76500 to 45375 W output over a range.
6. Motor torque (Nm) varies from 412.07 to 695.01 N.M.

So the designer has got the flexibility to choose whatever grade he wants from 6.5 up to 13.14, keeping all the inputs the same. Similarly, the motor output power can be varied from 45375 to 76500 W without compromising the acceleration performance. In fact, the motor power of 45375 W is itself enough to provide the acceleration that is needed by the traction motor.

Iteration 2: The designer decides, that the gradability of the vehicle should be greater than 10%. For the 2nd Iteration, the input and the output values are as follows in table 3 (also figure 41). Note that gradability is now an input, unlike the first iteration. Thus the inputs and outputs can be changed in between iterations.

It should be noted that the green color in some of the values is added externally so that the reader of this thesis is able to distinguish between the various (input –output) variables, it is not a part of the actual program.

Note that in the first iteration, gradability was an output; now in 2nd iteration, the designer is an input, as he wants to maintain certain minimum gradability. At the end of the 2nd iteration, the designer has satisfied all the requirements that were expected from the vehicle. The motor power was already enough for acceleration; because of the large battery, the designer had the freedom to ensure that the vehicle has as high gradability.

The one-dimensional plots for the first two iterations are shown in figure 42. The red colored points and bars are the first iteration, and the blue colored are the 2nd iteration. Not that, for the second iteration, the gradient is an input, and it shrinks the torque bar as well as the motor power bar.

Fig.41. Iteration 2 inputs-outputs for the point input range output scenario.

Table 3: Results after 2^{nd} iteration for point input- range output scenarios

Input Variable	**Value**
Acceleration time	10 seconds
Battery Power	70000 W.
Engine Generator Power	20000 W.
X	5
Vehicle Mass	1500 kg
Gear Ratio	6.6
Final Speed after acceleration	22 meters per second.
Battery energy Capacity	3 KWH
Variation in State of Charge	0.6 – 0.4
Vehicle Base Speed	10 meters per second.
Gradability	10%
Output Variable	Variable
Motor torque	559.78 – 695.01
Motor Power	76500-71117.06
Motor Base Speed	2100.3
Motor Maximum Speed	10516.
Change in Battery energy	1.8 –1.2

Again, as explained earlier, the bars shown in figure 42 on the next page are only of relevant variables. In fact, any of the design variables can be plotted as single dimensional plots. The designer is able to observe the relevant variables with clarity the variables that he needs to see as single dimensional plots.

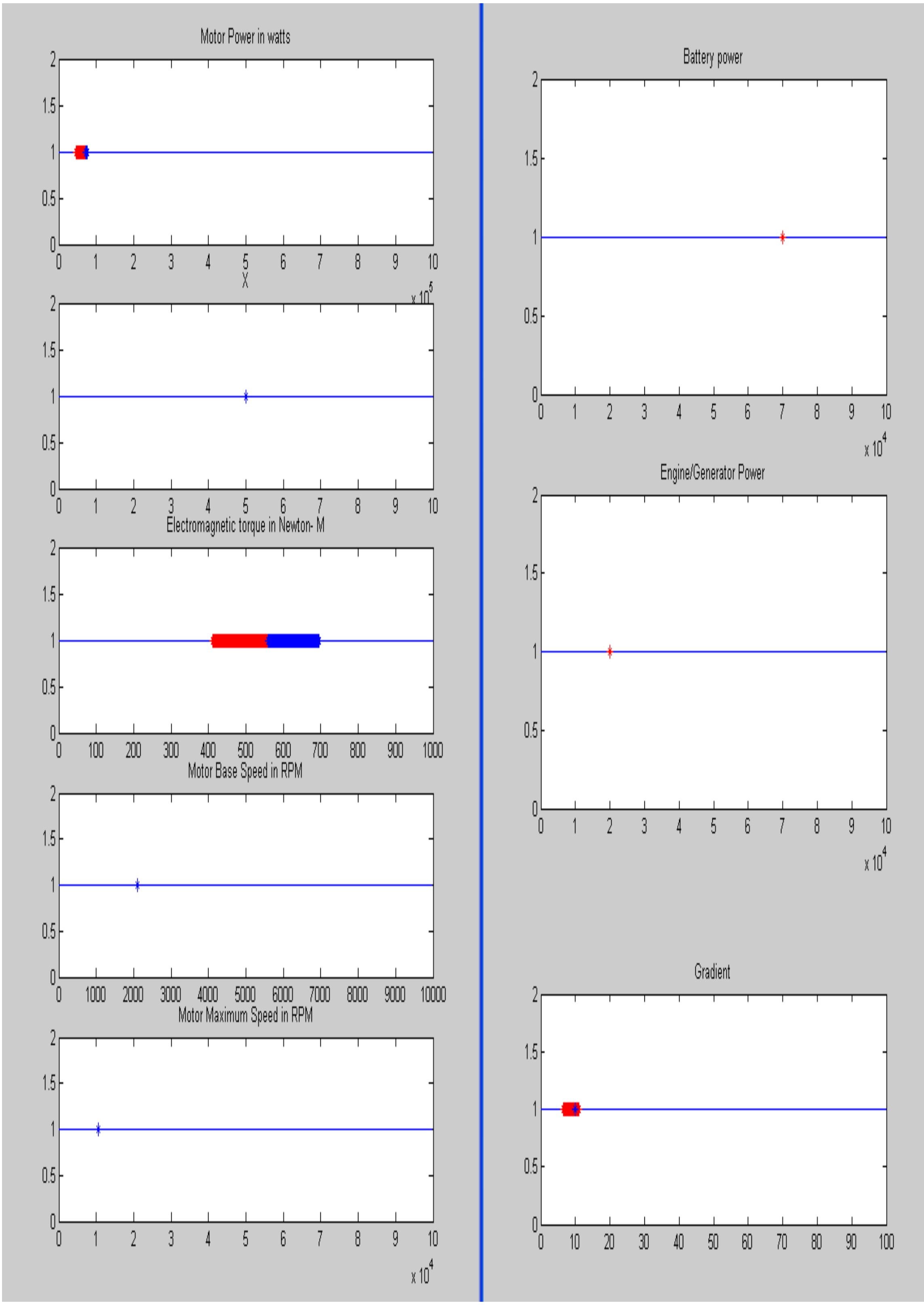


Fig.42. The one dimensional plots for the first two iterations

Now that all the design restrictions are satisfied, the designer realizes that he has as very big battery for no reason. So, for the last iteration, the designer decides to determine the actual battery size needed for the given gradability, and the lower of the two torque values. So for the third and final iteration, the input and the output variables are as shown in table 4:

Table 4: Results after 3rd iteration for point input- range output scenarios

Input Variable	**Value**
Acceleration time	10 seconds
Motor Power	71117.06 W.
Engine Generator Power	20000 W.
X	5.
Vehicle Mass	1500 kg
Gear Ratio	6.6
Final Speed after acceleration	22 meters per second.
Battery energy Capacity	3 KWH
Variation in State of Charge	0.6 – 0.4
Vehicle Base Speed	10 meters per second.
Gradability	10%
Output Variable	Variable
Motor torque	558.67
Battery Power	63667.12 W
Motor Base Speed	2100.3
Motor Maximum Speed	10516.
Change in Battery energy	1.8 –1.2

To summarize the steps followed by the designer for the three iterations,

1. At the end of the first iteration, the designer discovers that in spite of having given point inputs, he has got motor power, gradient as well as torque over a range .The designer decides to have a gradient of at least 10%.

2. So, in the 2nd iteration, he enters gradient as an input with the value of 10%. As expected, the minimum power rating has increased, narrowing the power range. The same happens with the torque range.The designer has all his needs satisfied by the minimum value of power (71.117 KW) and hence does not need the extra motor power. So to reduce the higher end of the motor power, he decides to reduce the battery power.

3. In Iteration 3, the designer enters the sufficient motor power (71.117 KW) and calculates the battery power that will be sufficient in providing him that much power. (figure 43).

This 3rd case study is very interesting because it involved all the scenarios: point in point out, range in range out, point in range out scenarios. The user starts with a point in range out scenario (Iteration 1) , and the proceeds to another point in range out scenario (Iteration 2) and as he gets to the final iteration, he does a point in point out scenario. One can now appreciate the fact that with a larger number of iterations, the designer will be able to handle many more such complex point in range out scenarios .For the given nature of the system, three iterations were thought to be sufficient, and this also made the length of the code smaller. Also, with more number of iterations, the user can take smaller and more precise steps towards the final design, for example, in the given case, the user could have decided the gradability twice, in smaller steps and arrived at the same conclusion.

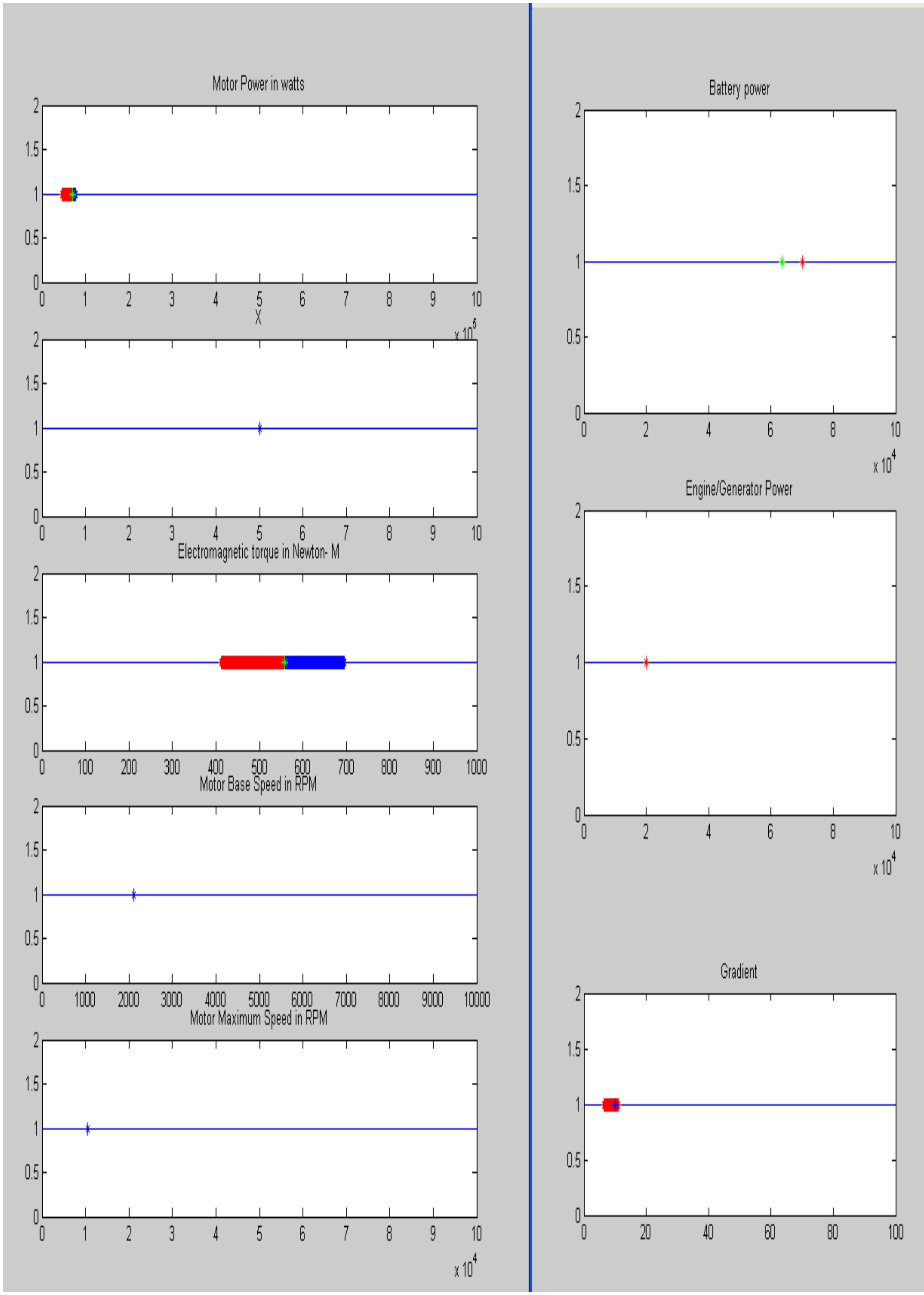


Fig.43. One dimensional plots for the three iterations (point in range out).

D. Summary

This chapter implemented the theory discussed in the earlier chapter. The software tool was introduced and used for the three scenarios. These bring out the utility of the tool.

CHAPTER VI

SUMMARY AND FUTURE WORK

A. Summary

There were two objectives of this thesis: the first, to develop a new approach towards design of complex systems and the second to create a software tool using this new approach. A series hybrid electric vehicle was chosen as the system for which design using this tool would be implemented.

The initial chapters laid out the theory of an HEV. The series hybrid was explained in detail. The series hybrid is a complex system, having many components, which interact with each other. These components interact or behave differently with each other at different intervals of time, depending on the control strategy that is being used. System level design of a series hybrid involves calculating or deciding the power and some other parameters of each component, so that those components would then work together to generate motion, and satisfy the performance conditions of the user.

The conventional design is essentially a uni-directional process, the designer starts from the performance specifications and works his way inwards to the component level design.

The omni directional design process is one in which the designer has the freedom to chose the desired set of inputs as the starting point. He can start from known values of different parameters in different components, or from any component of his choice. The design tool then completes the design for him by providing values for the unknown parameters, as the output. The designer is also able to provide ranges of parameters as inputs, if he is not sure of exact values for certain parameters. The tool is able to deal with scenarios in which the user gives point input or inputs over a range.

Point in – range out scenarios was also discussed, and examples of how such scenarios originate out of mathematical equations and physical restrictions were given. This tool is also able to deal with such scenarios, and the designer, in spite of giving point inputs, gets ranges at the output. This scenario is very interesting as it gives the designer freedom to choose one of the outputs out of an entire range available to him. He can then go further and design the power train for that particular output.

The three scenarios were discussed in detail as three design examples, which were performed using the tool. The functioning of the tool was explained along with these. The thesis also discussed the freedoms that are available to the user because of the new design approach, and how the freedoms can be used to further enhance the design process.

B. Future work

As explained in Chapter IV, this method of design has numerous applications. The omni – directional design, which has been limited to system level considerations for this project, could be extended to component level design. The design can have additional sets of equations that can be used for optimization reasons, like optimization of cost, power density amongst other things. This design can essentially be applied to any complex system, which can be described by mathematical equations. The present design can be enhanced by adding more number of iterations so that the designer can 'play around' in the design space much more and try and locate points suitable to him. Similarly, the power ratings of the components can be optimized for fuel economy or power density by adding those equations. This work can be applied to the design of a parallel hybrid, and can be taken down to the component level.

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VITA

Neeraj Shripad Shidore obtained his B.Eng. in electrical engineering from the Government College of Engineering, Pune, India. In the Fall of 2001, he began studying for his Master of Science in electrical engineering at Texas A&M University and received it in December 2003.

Neeraj Shripad Shidore

“Kamalkunj,” 111- Mayur Colony

Kothrud, Pune – 411029

Maharashtra, India.

The typist of this thesis was Mr. Neeraj Shidore.