Optimal Design of Battery-Ultracapacitor Hybrid Source Light/Heavy Electrified Vehicle

Seyed Mahdi Mousavi Sangdehi
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Optimal Design of Battery-Ultracapacitor Hybrid Source Light/Heavy Electrified Vehicle

By

Seyed Mahdi Mousavi Sangdehi

A Dissertation
Submitted to the Faculty of Graduate Studies through the Department of Electrical and Computer Engineering in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the University of Windsor

Windsor, Ontario, Canada

2015

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Optimal Design of Battery-Ultracapacitor Hybrid Sources Light/Heavy Duty Electrified Vehicle

by

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20/May/2015
I hereby declare that this thesis incorporates material that is result of joint research, as follows:

<table>
<thead>
<tr>
<th>Dissertation Chapter</th>
<th>Publication title/full citation</th>
<th>Publication status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 3</td>
<td>S. Hamidifar, S. M. Mousavi, and N.C. Kar, “Comprehensive Modeling of Electric Vehicles to Analyze Their Performance Based on Different Propulsion Profiles,” IEEE Transportation Electrification Conference and Expo (ITEC), vol. 1, no. 5, pp. 16-19, 2013.</td>
<td>Published</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>S. M. Mousavi Sangdehi, K. L. V. Iyer, K. Mukherjee, and N. C. Kar, &quot;Short term power demand forecasting in light- and heavy-duty electric vehicles through linear prediction method,&quot; IEEE Transportation Electrification Conference and Expo (ITEC), vol.1 , no. 6, pp. 18-20 2012.</td>
<td>Published</td>
</tr>
</tbody>
</table>


4. Collaboration with Saeedeh Hamidifar, Varahan Iyer, and Dr. Kuashik Mukherjee under supervision of prof. Narayan Kar covered in chapter 4. In all cases, the key ideas, experimental design and simulation were performed by the author, and the contribution of co-authors was through the analysis preparing the papers.

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ABSTRACT

This dissertation contributes to the optimal design of battery-ultracapacitor hybrid sources light/heavy duty electrified vehicle power-train architectures. Electrified vehicle (EV) in automotive technology is one of the major solutions to today’s environmental concerns such as air pollution and greenhouse effects. Light duty and heavy duty EVs can reduce the amount of the pollution effectively.

Since, in this area all researches deal with optimal cost of the system and rarely consider the regenenerate brake energy, the lack of comprehensive study on other important issues on optimal sizing including size, space, and acceleration time is feeling. Also it is necessary to be comparing with regenerate brake energy for battery and UC or both scenarios. Therefore the first part of this study consists of comprehensive optimization of a hybridized energy storage system including batteries and ultracapacitors considering a multi-objective function of cost, space, weight, and acceleration time.

In motor drive part of the power-train, a study on analyzing current topologies is essential and if possible any new design which results in better efficiency and harmonics distortion would be appreciated. So in the next part of this research which is the DC/AC motor drive, a novel motor drive with stacked matrix converter (SMC) was developed. This new design was compared with two other popular DC/AC inverters and was proved to be more efficient and an optimal match for the EV application.

In the last phase of this research, since the DC/DC converter deals with battery/UC hybrid sources and their energy management systems (EMS), it needs to be fast enough that can improve the dynamics of the system, but so far, very rare studies have been done to improve the DC/DC converter dynamics in EV applications. Therefore the need of applying prediction algorithms to modify the controller of DC/DC converter dynamics is feeling. Therefore, three different prediction algorithms were developed to be used as the predictive controller for the DC/DC
converter. Linear prediction as one of the fast and precise prediction algorithms were applied and modified.
DEDICATION

To my parents, Seyed Mohammadreza and Seyedeh Mansoureh, who have been the best support systems of my life.
ACKNOWLEDGEMENTS

First and foremost, I have to thank my research supervisor, Prof. Narayan Kar. Without his assistance and dedicated involvement in every step throughout the process, this dissertation would have never been accomplished. I would like to thank him very much for his support and understanding over these past five years. I would also like to show gratitude to my committee, including Dr. Kemal Tepe, Dr. Esam Abdel-Raheem, Dr. Walid Abdul-Kader, and Dr. Shaahin Filizadeh. My friends Foad Samadi, and Mahdi Alavi, at the University of Windsor kindly assisted me with this dissertation and were very patient with me.

Getting through my dissertation required more than academic support, and I have many, many people to thank for listening to and, at times, having to tolerate me over the past five years. I cannot begin to express my gratitude and appreciation for their friendship. Farshad, Aiswarya, Aida, Shruthi, Hima, Nikola, and Eshaan have been unwavering in their personal and professional support during the time I spent at the University. For many memorable evenings out and in, I must thank everyone above as well as Mostafa, Javad and Shirin.

Most importantly, none of this could have happened without my family. To my parents and my brothers and my lovable nephews— it would be an understatement to say that, as a family, we have experienced some ups and downs in the past five years. Every time I needed you, you support me and I am forever grateful. This dissertation stands as a testament to your unconditional love and encouragement.
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NOMENCLATURE

\( \eta_{\text{inv}} \): Inverter efficiency, set to 0.9

\( DOD \): Depth of discharge

\( SOC_{\text{bat}} \): State of charge of battery

\( SOC_{\text{uc}} \): State of charge of Ultracapacitor (UC)

\( P_{\text{T,bat}}^{\text{max}} \): Maximum power limitations for batteries [Watt]

\( P_{\text{T,bat}}^{\text{min}} \): Minimum power limitations for batteries [Watt]

\( P_{\text{T,uc}}^{\text{max}} \): Maximum power limitations for UCs [Watt]

\( P_{\text{T,uc}}^{\text{min}} \): Minimum power limitations for UCs [Watt]

\( K_{\text{bat}} \): Battery dynamic coefficient

\( \eta_{\text{inv-rev}} \): Reverse direction efficiency of inverter

\( P_{\text{load,uc}}^i \): Load allocated to UC in each time step [Watt]

\( P_{\text{load,bat}}^i \): Load allocated to battery in each time step [Watt]

\( K_{\text{cost}} \): Coefficient of cost

\( K_{\text{space}} \): Coefficient of space

\( K_{\text{weight}} \): Coefficient of weight

\( K_{\text{accel.}} \): Coefficient of acceleration

\( N_{\text{uc}} \): Number of UC cells

\( N_{\text{bat}} \): Number of battery cells

\( N_{\text{inv}} \): Number of inverters

\( C_{\text{uc}} \): Cost of each UC cell [$]

\( C_{\text{bat}} \): Cost of each battery cell [$]

\( C_{\text{inv}} \): Cost of each inverter [$]

\( M_{\text{uc}} \): Maintenance cost of each UC cell [$]

\( M_{\text{bat}} \): Maintenance cost of each battery cell [$]

\( M_{\text{inv}} \): Maintenance cost of each inverter [$]

\( Y_{\text{uc}} \): Number of UC replacement times according to EV and UC life time

\( Y_{\text{bat}} \): Number of battery replacement times according to EV and battery life time

\( Y_{\text{inv}} \): Number of inverter replacement times according to EV and inverter life time

\( S_{\text{uc}} \): Volume of each UC cell [cm\(^3\)]

\( S_{\text{bat}} \): Volume of each battery cell [cm\(^3\)]

\( W_{\text{uc}} \): Weight of each UC cell [kg]

\( W_{\text{bat}} \): Weight of each battery cell [kg]

\( f(N_{\text{uc}}) \): Function of number of UC cells

\( U \): Matrix for initial values of PSO variables

\( b_{lo} \): Lower band of the PSO variables
\(b_{up}\) : Higher band of PSO variables
\(P_i\) : Particles position in each iteration of the PSO optimization
\(g\) : Particles best position
\(x_k\) : Each particle distance from the current position
\(v_k\) : Particle velocity
\(w_k\) : Inertia weight
\(f(x_i)\) : Objective function value in each iteration
\(f(p_i)\) : Best value of objective function in each iteration
\(THD\) : Total harmonic distortion
\(H_1\) : Fundamental
\(H_n\) : Nth harmonic
\(P_{SW}\) : Switch loss [Watt]
\(P_D\) : Diode loss [Watt]
\(\nu\) : Instantaneous voltage [V]
\(i\) : Instantaneous current [A]
\(T\) : Switching time period [S]
\(P_T\) : Total losses in the converter [Watt]
\(\eta\) : Converter efficiency
\(P_i\) : Converter input power [Watt]
\(P_{out}\) : Converter output power [Watt]
\(E\) : Battery voltage [V]
\(D_{clamp}\) : Clamped diode
\(R_{SW}\) : Approximate on-state switch resistance slope [ohm]
\(V_{SW}\) : Instantaneous switch voltage [V]
\(i_{SW}\) : Instantaneous switch current [A]
\(V_{SW, sat}\) : Forward voltage drop across the switch [V]
\(R_{SW}\) : Switch conducting resistance [ohm]
\(V_{F0}\) : Forward voltage drop across the diode [V]
\(I_F\) : Diode forward current [A]
\(R_F\) : On-state resistance of the diode [ohm]
\(V_{as,b,c,s}\) : Output line-to-neutral voltage of inverter [V]
\(V_{ab,bc,ca}\) : Output line-to-line voltage of inverter [V]
CHAPTER 1

Introduction and Literature Review

The important design challenges in electrified vehicle powertrain with hybrid energy storage systems lie in optimal sizing of the sources, DC/DC converter controller, and motor drive designs to interface between the energy systems and electric motor to meet the desired demand with improved performance. Combined usage of multiple energy storage systems in an electrified vehicle permits the system to exploit the different sources in proper time to increase the system efficiency. However, to obtain high utilization efficiencies, the power electronic interface, including the DC/DC converter and the DC/AC motor drive, play an important role in electric vehicles powertrain. As such, a novel design of a powertrain system excluding the motor is required to transfer and share the demanded power from motor to energy sources with the best desired efficiency. This thesis addresses the optimal design of the powertrain of an electric vehicle by optimal sizing of the hybrid sources and a novel predictive controller of DC/DC converter in power sources side and by developing a novel design of the DC/AC Drive with better performance in the motor side. To begin, this chapter provides an introduction to the applied research of all three phases of this project including hybrid sources, DC/DC controller, and DC/AC motor drives in electrified vehicles. The overall electrified vehicle schematic is depicted in Figure 1.1.

![Figure 1.1. The overall system schematic.](image)
1.1 Overview

The continuously depleting state of the health of the environment has pushed researchers to conduct a comprehensive estimation of fuel-cycle emissions and energy use at the global level. Studies indicate that the increase of the CO$_2$ emission accounted by transportation is about 22% from 14 billion tons to 31 billion tons over the past 30 years. Globally, private transport takes up 50% of the oil consumption and contributes to 77% of carbon monoxide and 49% of nitrogen oxide emissions [3]. The rate of greenhouse gas emission, along with the growing demand for fossil fuels in the world has promoted the need for alternative transportation fuels and advanced vehicle technologies. The transition from traditional internal combustion (IC) engines to Electrified Vehicles (EVs) creates a major impact on oil dependence and results in sustainable transportation with improved environmental conditions. This awareness has led to the development of an era of electrified transportation. Major automakers, including General Motors, Toyota, Ford, Mercedes, Volvo, BMW, and Nissan are investing in the development of new generation of energy efficient cars called Extended Range Electric Vehicles (EREV), plug-in hybrid electric vehicles (PHEVs), and all-battery electric vehicles (BEVs). Furthermore, Tesla Motors, one of the major shareholders of the electric vehicle transport industry, ship BEVs [1]. As the leading names in auto industry compete to market high performance electric and hybrid electric vehicles, Canadian consumers now have a wide selection of hybrid/electric models to choose from. Consumers can make their choice of the vehicle based on the all-electric driving range, fuel consumption, economics, acceleration and thus the overall efficiency of the vehicle. Advancement in the overall vehicle performance through the above factors depends on improvement in each of its drive-train components and the overall design and energy management between the components.

There are two major sources of energy storage systems in electrified vehicles namely charge sustaining and charge depleting. Charge depleting implies a system in which the state of charge (SOC) declines while the vehicle operates. This imposes limitations on the system’s operational range. In such systems, optimal design of the electrified vehicle
considering optimal sizing and optimal design of power-train is necessary as it results in extending the operating range.

The proposed electrified vehicle with hybrid sources including at least one depleting charge energy source (battery-ultra-capacitor) will be designed optimally. It embraces applying energy management strategies for optimal sizing of hybrid sources and optimal design of power train including the DC/DC and DC/AC converters.

As it can be seen in Figure 1.2, the power-train composed of 3 different parts which need to be modified in order to achieve better results. According to previous explanation in abstract, the hybrid sources EVs need a comprehensive optimization considering all customer and manufacturer points of view including size, weight, and acceleration time. Also regenerate brake energy should be considered in this analysis. Also DC/AC motor drive is playing an important role in power-train systems, so it needs to be improved either in control or design. A comprehensive analysis of different topologies in this area is essential. Moreover, DC/DC converter which deals with hybrid power sources needs to be fast enough to increase the dynamics of the system. So, to improve the power train of electrified vehicles, improving the power electronic module is the most effective. Hence, in order to achieve better performance, the optimal design of all the power sources,
DC/DC converter and the DC/AC converter is of utmost importance. With this regard, optimal sizing of power sources, a novel optimal design of motor drive, and a prediction-based DC/DC converter controller will be designed in this study to make the overall system work more efficiently.

1.2 Optimal Sizing of Hybrid Sources in Electrified Vehicles

Designing an optimized energy management strategy is of paramount importance and goes hand-in-hand with the overall development of the vehicle even if there are highly efficient components in the drive-train, utilizing them in an inefficient manner will deteriorate the entire objective of vehicle development. The energy sources and their management in an electrified vehicle continue to be a major challenge for automakers to extend the all-electric driving range. Energy sources in commercially available electrified vehicles are generally a battery module, an ultracapacitor (UC) module, or a combination of both [2]. Generally, batteries have higher specific energy than ultra-capacitors, and hence, can provide extra power for longer periods of time. An ultracapacitor typically has higher specific power than a battery, is more efficient, and has a longer lifetime in terms of the number of charge/discharge cycles [3]. Moreover, in order to perform optimal powertrain design, emphasis is placed on advanced, compact, high energy-density electrical storage systems, to provide both high power and high energy. A combination of multiple types of energy storage, such as batteries combined with ultracapacitors, may provide the best overall performance and offer superior power, energy, and cycle life. Also, an optimized energy management between these devices will enable the reduction of battery usage and improve its life span [4]-[11].

Previous research presented in [4], [5], [12]-[16] mainly focused on different motor drives, control schemes and their optimization for improvement in the overall efficiency of the vehicle. Different hybrid sources of energy including fuel cells, UCs, batteries, and photovoltaic arrays were applied and the vehicle’s performance was analyzed in [8], [17]-[19]. Background literature obtained from [4]-[19] show that research performed to date on energy management systems in electric vehicle/hybrid electric vehicle (EV/HEV)
employed the micro-level analysis by focusing in-depth on a particular part of the entire drive-train. However, a macro level analysis of hybrid energy sources was not performed. In order to effect a comprehensive macro level optimization, it is imperative to consider optimal sizing of hybrid energy sources, without hampering the desired characteristics of the vehicle. The challenge lies in designing an optimized energy management strategy based on cost, space, weight and acceleration time of the vehicle for proper utilization of the hybrid energy sources and thus improving the overall efficiency and economics of the vehicle. Understanding the importance of designing an optimized drive-train system with hybrid energy sources, this research firstly presents a novel swarm intelligence based off-line energy management strategy (EMS) for optimal sizing of battery/ultracapacitor hybrid energy sources in EV/HEV.

Optimizing the hybrid power sources will be slightly different. If the configuration of the hybrid power sources change, therefore the optimization strategy will be changing in constraints over the DC link and charge/discharge strategy. All possible battery/UC configurations have been explained in Figures 1.3 to 1.7. in this study the optimization has been applied on Figure 1.7 strategy [20].

Figure 1.3. Conventional schematics of hybrid energy storage systems

Figure 1.4. Modified conventional schematics.
Figure 1.5. Cascaded schematics of hybrid energy storage systems.

Figure 1.6. Conventional schematics of hybrid energy storage systems using two bidirectional converters.

Figure 1.7. Multiple inputs schematics of hybrid energy storage systems.
Figure 1.3 shows the conventional schematic of a hybrid energy storage system. By using a bi-directional DC/DC converter to link the ultracapacitor and the battery, the UC voltage can be varied over a wide range. Moreover, the UC banks nominal voltage can be lower than the DC link. Since the battery is connected to the DC link directly, the voltage of the DC link can be maintained relatively constant. However, this configuration has certain disadvantages. As the UC can only partially absorb the regenerative braking energy, smooth control is not obtained. Moreover, a large size bidirectional converter is required in order to effectively handle the power of UC.

If the position of the battery and UC are switched in the UC/battery configuration, the new battery/UC configuration [20] is obtained as shown in Figure 1.4. In this configuration, the battery voltage can be maintained lower. As the ultra-capacitor is connected to the DC link directly, it also works as a low pass filter. This topology allows the voltage of the DC link to fluctuate in a range, which leads the ultra-capacitor to work in a wider range.

To improve the working range of the ultra-capacitor in the battery/UC configuration, an extra bi-directional DC/DC converter can be added between the ultra-capacitor bank and the DC link. This results in a cascaded converter topology as depicted in Figure 1.5.

Figure 1.6 presents an alternate topology for the cascaded connection of two bi-directional converters. In this configuration, the outputs of the two converters are connected in parallel and hence these converters will maintain the same voltage level as that of the DC link. One of the major benefits of this topology is that the rated voltage of both the battery and the ultracapacitor can be maintained at a lower value when compared to the DC link. So the ultracapacitor voltage can vary over a wide range and it results in full usage of the capacitors. The only disadvantage of this configuration is that two converters are used.

In order to avoid the usage of two bi-directional converters to interface the battery and the ultracapacitor, a multiple input converter configuration is implemented as shown in Figure 1.7. Multiple input converters are a better solution to reduce the total cost of the cascaded converter connection.
Understanding the above topologies, it is clear that the multiple input configuration is the best arrangement of the battery and the ultra-capacitor hybrid sources in electrified vehicles. Thus, further investigation on the sizing of energy sources used in EVs will take into account this converter arrangement.

The following conclusions can hence be noted from the above analysis:

- In order to make a comprehensive macro level optimization, it is imperative to consider optimal sizing of hybrid energy sources, without hampering the desired characteristics of the vehicle
- Multi-objective optimization based on vital constraints for hybrid energy sources such as cost, space, weight and acceleration time of the vehicle for efficient selection of optimal sizing is required.

1.3 Predictive Controller (PC) Design of DC/DC Boost Converter

The current market of light electric vehicles (cars) and evolution of all electric heavy-duty vehicles (buses) in the market like the e-BUS12, Proterra, Astonbus, etc. has accelerated the need for advanced research and development of fastest energy management system (EMS) of these vehicles for better utilization of battery/ultracapacitor combination considering frequent stop/start duty. Considering this type of duty, the efficiency of these vehicles can be enhanced by assisting the energy management system with pre-emptive knowledge of power demand, which can lead to effective and efficient utilization of the vehicle’s powertrain. The prediction scheme proposed in this section assists the energy management system by forecasting the load demand based on frequently updated history of the vehicle. Moreover, the real-time application of such prediction schemes performed at the Audi Research Labs to improve the fuel economy of Internal Combustion Engine (ICE) based vehicles has led to the application of these schemes for light as well as heavy-duty electric vehicles. Using the knowledge of traffic ahead, the EMS in the vehicle can react to changes in traffic density or speed before they happen, enhancing the response time of various components and hence the efficiency of a trip. Background literature obtained from [21]-[23] illustrates that the EMS of electric and hybrid electric vehicles require prediction times in the range
of seconds ahead of interest as the problems associated with delay due to vehicle
dynamics have to be dealt with. Thus, short term demand prediction can be used as a tool
towards improved dynamic control of these vehicles by making short-term decisions. The
short-term decisions could be either changing from one power source to the other in a
HEV, or changing the power flow among the different hybrid sources in an electric
vehicle and/or any other control action which involves delays. Therefore the predictive
controller will help the DC/DC converter to improve its dynamic to be fast enough to
meet the demanded power faster. Figure 1.8 depicts a general schematic of a DC/DC
converter, which has the main role in power distribution among hybrid sources [24].
These components values have been used in Appendix F to calculate the DC/DC boost
converter’s dynamic model using an averaging technique. This can be used for designing
the observer-based controllers. This technique in this study has not been used. Figure 1.8
has been depicted to express the state space modeling technique in a very simple format
since it is depicting the simple boost converter. In this study the data of demanded power
has been captured from a real drive cycle and has been used to form the prediction model
of the system for using in prediction based controller. Prediction based controller can be
done for all DC/DC configurations in Figures 1.3 to 1.7 based on either system dynamic
modeling or the data captured from the system to design a model of forecasting.
Therefore a typical DC/DC boost converter as it is shown in figure 1.8 has been used in
this study in appendices. For the first method, state space model of the DC/DC converter
using of average technique is used. Then any estimation technique such as filters like
robust filters or sliding mode algorithm can be used to estimate the system states.

Figure 1.8. Schematic of DC-DC boost converter.
The other method, which is based on data acquisition system uses different prediction techniques but linear prediction algorithm to predict the system states is the most powerful tool of prediction and will be used in this study as the base of prediction. Thus, using the prediction based method; the following issues need to be addressed in this area:

- Most of the prediction algorithms used so far have failed to consider filtering the out-of-range data, which influence the accuracy of the prediction to a great extent;
- Scanty research on optimized linear prediction method;
- Optimized linear method will increase the accuracy of the forecast and subsequently resulting in better system efficiency;
- Faster dynamics of the system will result in enhanced performance. Owing to the one step ahead predictive controller, the system response time to an event will decrease.

### 1.4 Motor Drive Optimal Design

The rapidly growing global demand for Electric Vehicles (EV) over the recent years has inspired EV designers towards developing more optimal EV systems [21]-[25]. Motor drive system is one of the most important components in an electric vehicle structure, which has strong influence on the whole system performance. Therefore, many configurations and topologies for the power converters are proposed by researchers to address inclusion of the most proper converter configuration into the EV drivetrain [26]-[29]. Multilevel converters are considered as an inevitable choice with respect to their merits including low-distortion voltage and current characteristics, low output voltage deviation, low switching frequency, and small common mode voltage that results in lower stress on motor bearings [30]-[33].

The first multilevel converter was designed as a three-level, three-phase device in 1975 [34]. However, multilevel converters were employed in EV structure only in the last decade [35]. In spite of the fact that the multilevel converters are widely used in EV/HEV structures, their major drawback is that the system consists of several power semiconductor switches resulting in less efficient converters due to switching power loss.
Therefore, in [36], The authors have reduced the voltage to overcome the switching power dissipation issue. In [37]-[40], the authors carried out investigations on different converter topologies for 7 to 15 different output voltage levels. The authors in [41] conducted a comprehensive study to investigate the effect of DC input voltage variations due to the battery state-of-charge reduction for three converter topologies in EV applications. As an alternative approach to achieve efficient converter topologies, the effect of control strategies such as space vector modulation and pulse width modulation (PWM) were investigated in [42]-[44]. Authors in [45]-[48] proposed a modified diode-clamped converter design to improve the DC/AC converter performance.

Based on the switching algorithm and other aspects such as any voltage levels, closed loop control strategies, there are several topologies of DC/AC converters with their specific characteristics such as diode-clamped, flying capacitor, H-bridge, matrix converters, and cascaded inverters. Flying capacitor converter with easier extension of the voltage level to higher levels has also some disadvantages. These converters include large capacitor banks, and an additional pre-charging circuitry. Also voltage imbalance among flying capacitors is an important issue in this converter.
Cascade inverters are proper converters for medium voltage, high power applications. But based on their configurations, they are more complicated than other types of converters and also more expensive. Therefore, in a diode-clamped converter, there is simplicity in extending the voltage to higher levels, and is widely used in medium and low power applications. In this study the proposed Stacked Matrix Converter (SMC) converter has been compared with neutral point clamped (NPC) or diode-clamped converter. Also currently, H-bridge converter is the simplest and cheapest converter for driving AC motors in different power range. Therefore, manufacturers in auto industry prefer to use H-bridge converter unless a new converter with advantages that can outperform the H-bridge is simple structure, emerges.

Also, in spite of all the investigations carried out on different DC/AC converter topologies in electric vehicle applications, the lack of sufficient studies on the matrix converter (MC) topology is apparent. Moreover, from an EV manufacturers’ perspective, a comprehensive study on efficiency and performance of different motor drive configurations is required. Therefore, this section introduces a new design developed based on indirect matrix converter and compared it to both diode-clamped and H-bridge converter that are being increasingly used in industry.

Figure 1.9 shows a general schematic diagram of an indirect matrix converter. This topology benefits from better output voltage stability and less total harmonic distortion (THD) compared to other existing converter topologies. MC is inherently bi-directional that can regenerate energy. This converter has also the advantage of variable output voltage and frequency generation. In this research a new stacked matrix converter (SMC) is designed and developed. The proposed configuration not only possesses all the good features of MCs but also a reduced number of switches has led to a simpler design, more cost effective system, and more efficient structure with lower power dissipation.

It should be noted that there are different types of motor drives including flying capacitor and cascaded inverters. Since other types of inverters are not proper choices of DC/AC motor drive in electrified applications they are not explain here. For example, cascaded inverters are too bulky and expensive to be used in the electrified vehicles and
flying capacitors are not proper enough to be used in the electrified vehicles since they have large capacitors and their control strategies are complicated.

As motor drive is a critical component of the power train design of the EV system, it is crucial to consider the following issues:

- The lack of sufficient studies on matrix converter (MC), which could be a better topology compared to the conventional one, due to its bi-directional switch design; and
- A comprehensive study on efficiency and performance of the entire system including motor, drive and energy storage system is still missing.

1.5 Motivation for This Dissertation

This research is motivated by the idea that electric vehicles represent not only an economical but also a green-house gasses (GHG) free and technically feasible solution for future transportation systems. Environmental effects, rising prices of petroleum based fuels, emission limitations, and the reduction of natural resources provide convincing motivation towards the development of electrified vehicles (EV). In addition to sustaining Canada’s policy objectives and meeting the Kyoto obligations to reduce greenhouse gas (GHG) emissions, innovations in electric vehicular technology contribute to the concept of sustainable development. ‘Sustainable Development’ has been defined in all fields as, “meeting the needs of the present without compromising the ability of future generations to meet their own needs [5].”

This represents one of the greatest challenges of today, a challenge that calls for responsible development of technology. Addressing these challenges will apply several areas of research to be investigated. One of the important and effective areas is developments in electrified vehicle technology.

The demand for higher power and torque in automobiles let to general attraction of people towards the internal combustion engine (ICE) as compared to EV for road vehicular purposes.
Moreover electric powertrain is superior according to performance and energy conversion efficiency, but the only restrictive factor remains the limitation of energy storage systems. Battery powered vehicles simply could not meet the high-energy density due to their low dynamics, plentiful supply and logistical attributes of petroleum based propulsion [2]. Considering the ICE energy conversion efficiency of below 20%, the energy density (Joules/kg) of petroleum extremely exceeds the energy density of all known battery technologies. On the other hand, cautiously recoverable petroleum deposits are going to be diminished, and the automobile number is increasing, causing cities to become overfilled with toxic hydrocarbons and its products. Therefore, the ICE is becoming a main source of GHG products.

Based on all issues mentioned above, the essential need of EV application in transportation is obvious. But according to the EV application, designing an optimal power-train to improve the efficiency as well as keeping the cost and design parameters optimal. Since power train of EV includes power sources, DC/DC converter and DC/AC motor drive, the first step to achieve an optimal design is optimal sizing of power sources based on a comprehensive design objective function. Next an important factor to improve the performance of EV is to overcome the low dynamics of the system. Therefore prediction based controller can be one the proper solution. With this regard many algorithms can be used, but applying the simple and fast algorithm with an acceptable accuracy is so challenging. To achieve this, a linear algorithm will be used for forecasting and some improvement will be applied on this later.

Finally the last and the most important part of power train is the motor drive converter, to improve the performance of the system a new design of three phase DC/AC converter has been developed. Compared to other available design, the proposed motor drive meets the EV requirement better than the others.

1.6 Dissertation Objectives and Contribution to Knowledge

The objective of this dissertation is to investigate an optimal design of electrified vehicle power train including three parts of power sources, DC/DC converter and DC/AC motor drive converter. More specially, these objectives include the following:
• Develop a comprehensive objective function including all design aspects, form all the technical design constraints, and applying the improved particle swarm intelligent (IPSO) algorithm to achieve the optimal sizing of hybrid power sources of battery and ultra-capacitor.

• Improve the dynamics of the system by applying prediction based controller to DC/DC converter. Using of linear prediction as a basic forecasting algorithm and proposed modifying linear algorithm including optimized linear prediction and Markov chain based linear prediction to make the system dynamic faster.

• Design a better motor drive DC/AC converter, which results in lower harmonics and harmonics loss, simple design and more economic system.

The contribution of this work can be summarized as follow:

• Based on the background studies in this area and expressing the unsolved issues, the design of electric vehicle can be modified significantly if its powertrain improved by three important parts:

  1. Energy storage; battery and ultra-capacitor based hybrid ESS has been chosen in this study

  2. DC/DC converters considering any design

  3. DC/AC converters including any available design

To achieve all the goals, the following contributions have been achieved:

Novel powertrain design of EV with higher efficiency, faster dynamics and optimal configuration based on following contributions:

  1. Optimal configuration of hybrid sources using of new energy management scenarios and improved particle swarm optimization.

  2. Design of optimal configuration of hybrid sources in a way that is fast enough (within seconds) if it is used as an online energy management system in EV.
3. Novel prediction based control strategies with high accuracy and low error of prediction to increase the efficiency of the system by improving the dynamics of the system.

4. Design a novel DC/AC converter with better performance including lower total harmonic distortion, voltage stability and lower loss.

5. Comprehensive analysis of novel design with other common converters in all technical and economic aspects.

1.7 Dissertation Layout

Chapter 2 begins with introducing the multiple objective function of the proposed EMS, and presents the complete formulation of the optimization scheme including all the constraints, which will be explained later. Later in this chapter, providing flexibility to the automaker in deciding the type of regeneration in the vehicle, the proposed energy management scheme is tested for three different scenarios: without regenerative braking; considering regenerative braking with UCs; and considering regenerative braking with UCs and batteries. Next it presents the validation of the developed energy management strategy. The results obtained from experiments conducted on an in-house electric vehicle are used as inputs to the developed EMS. The developed optimized swarm intelligence based energy management system is compared with an un-optimized wavelet based EMS. Also, sensitivity analysis was performed to bring out the merits of the developed EMS. This follows by presenting the validation of optimal sizing for an EV, modeled in vehicle simulation software and finally, justification of the optimal sizing for EMS scenario considered has been performed in a real-time simulator in order to prove the acceptability of the EMS in a real vehicle scenario.

Chapter 3 discusses different prediction algorithms which have been developed for this work. The chapter provides a theoretical background on linear prediction algorithm as well as the modelling of this algorithm with experimental data verification. Focusing on the improvement of the prediction results, two novel linear predictions including optimized linear prediction and Markov-chain based linear prediction are presented.
Simulations of proposed algorithms have been developed and compared with the conventional linear prediction with same experimental data. Finally, all methods MAPE (Mean Absolute Percentage Error) and MSE (Mean Square Error) have been calculated as a tool of comparison.

Chapter 4 presents an assessment of the performance of the proposed multilevel converter topology for EV applications, three-phase three-level diode clamped and H-bridge converters. It begins with a comprehensive study to investigate the effect of each configuration on EV performance. Later, the three converter topologies are introduced in detail. This follows by presenting the numerical investigation results on time, harmonic, and efficiency analyses. Next it presents the experimental results obtained by conducting several tests on the proposed SMC and diode clamped converters.

Chapter 5 concludes this dissertation with a general summary of the contributions and offers some remarks and suggestions on the way forward. Key areas that require further investigations are also presented in this chapter.

The Appendix section provides detailed switching tables of three motor drive topologies and correlation formulation to verify the prediction algorithms of this work.
Chapter 2

Optimal Sizing of Hybrid Sources in Electrified Vehicles

2.1 Introduction

Due to electric vehicle’s merits in GHG emissions comparing to internal combustion engine vehicles, electricity became transportation fuel imminent. Based on much advancement in electric and hybrid electric vehicles technology and different products of many automakers in this area, EV and HEV customers have a wide selection in accordance to their desired factors of EV and HEV purchasing [1].

As the leading names in auto industry compete to market high performance electric and hybrid electric vehicles, Canadian consumers now have a wide selection of hybrid/electric models to choose from. Consumers would make their choice of the vehicle based on the all-electric driving range, fuel consumption, economics, acceleration and thus the overall efficiency of the vehicle. Advancement in the overall vehicle performance through the above factors depends on improvement in each of its drive-train components and the overall design and energy management between the components. Designing an optimized energy management strategy is of paramount importance and goes hand-in hand in the overall development of the vehicle as even if there are highly efficient components in the drive-train, utilizing them in an inefficient manner will pull down the entire objective of vehicle development. The energy sources and their management in an electrified vehicle continue to be a major challenge for automakers to extend the all-electric driving range. Energy source in commercially available electrified vehicles is generally a battery module, an ultracapacitor (UC) module, or a combination of both [2]. Generally, batteries have higher specific energy than ultra-capacitors, and hence, can provide extra power for longer periods of time. An ultracapacitor typically depicts higher specific power than a battery, is more efficient, and has a longer lifetime in terms of number of charge/discharge cycles [3]. To achieve the best performance of EV/HEV technology in its power-train design, many researches have been done on high energy and power density electrical storage system. Therefore, a combination of multiple
types of energy storage including high power and energy density to provide the best performance on power, energy and overall efficiency is desired. Due to this, battery and ultracapacitor could be a proper combination of high power and energy density if an optimized energy managements system applied on that. [4]-[11].

Previous research presented in [4], [5], [12]-[17] mainly focused on different motors drives, control schemes and their optimization for improvement in the overall efficiency of the vehicle. Different hybrid sources of energy including fuel cells, UCs, batteries, and photovoltaic arrays were applied and the vehicle’s performance was analyzed in [8], [18]-[20]. Background literature obtained from [4]-[20] show that research performed till date on energy management system in electric vehicle/hybrid electric vehicle (EV/HEV) employed the micro-level analysis by focusing in-depth on a particular part of the entire drive-train. However, a macro level analysis of hybrid energy sources in sizing of them was not performed. In order to effect a comprehensive macro level optimization, it is imperative to consider optimal sizing of hybrid energy sources, without hampering the desired characteristics of the vehicle. The challenge lies in designing an optimized energy management strategy based on cost, space, weight and acceleration time of the vehicle for proper utilization of the hybrid energy sources and thus improving the overall efficiency and economics of the vehicle. Understanding the importance of designing an optimized drive-train system with hybrid energy sources, this section presents a novel study of battery-ultracapacitor based electric vehicle through comprehensive energy management strategies and improved swarm intelligence optimal sizing. This particle swarm optimization technique with a multiple objective function of cost, space, weight, and acceleration time has been applied to the proposed energy management strategy expressed in Figure 2.1. The novelty of this section is the comprehensive analysis of performance through a detailed objective function that includes cost, space, weight, and acceleration time for three energy management scenarios of this sizing application.

Particle swarm optimization (PSO) is simple in concept. It has few parameters to adjust and is easy to implement. In the past several years, PSO has been successfully applied in many research and application areas. In general, all the application areas that the other evolutionary application techniques are good at are the application areas for PSO. PSO has fast convergence speed over other stochastic methods. Also, PSO can be easily
modified by adjusting its cognitive coefficients which results in a much faster convergence time.

Section 2.2 introduces the multiple objective function of the proposed EMS, and presents the complete formulation of the optimization scheme including all the constraints mentioned above. Providing flexibility to the automaker in deciding the type of regeneration in the vehicle, the proposed energy management scheme is tested in section 2.3 for three different scenarios: without regenerative braking; considering regenerative braking with UCs; and considering regenerative braking with UCs and batteries. Section 2.4- 2.6 presents the validation of the developed energy management strategy. The results obtained from experiments conducted on an in-house electric vehicle are used as inputs to the developed EMS. The developed optimized swarm intelligence based energy management system is compared with an un-optimized wavelet based EMS. Also, sensitivity analysis was performed to extract the merits of the developed EMS. Section 2.7 presents validation of optimal sizing for an EV, modeled in vehicle simulation software and in section 2.8, justification of the optimal sizing for EMS scenario considered has been performed in a real-time simulator in order to prove the acceptability of the EMS in a real vehicle scenario.

2.2 **Formulation of the Optimization Problem**

A multiple objective function for the PSO based energy management strategy is developed here. Multiple objective functions embrace minimizing the cost, space, and weight of the energy generation system plus the acceleration time. The multiple objective function is formulated to optimize the hybrid energy sources, accounting for design factors such as the costs of the battery and the UC, space and weight of the hybrid energy sources, and the acceleration time of the vehicle, which varies with vehicle mass and all forces applied to vehicle plus the amount of UCs in EVs. But in this section the acceleration time function simply considered as the function of the number of UCs. Also, it maximizes the battery and UC’s life by monitoring and controlling their charge and discharge process. The objective function developed here, can be used for any multiple energy source combination. Also, various scenarios with or without each of the above mentioned objectives can be modeled using the same function. Numerical investigations
corroborating this claim are performed for five cases. The multiple objective function can be expressed as follows:

\[ f_{\text{Cost, Space, Weight, Accel. time}}(N_{\text{bat}}, N_{\text{uc}}) = K_{\text{cost}}F_{\text{cost}} + K_{\text{weight}}F_{\text{weight}} + K_{\text{space}}F_{\text{space}} + K_{\text{accel}}F_{\text{time}} \]  

(2.1)

where,

\[ F_{\text{cost}} = N_{\text{uc}}C_{\text{uc}}(Y_{\text{uc}} + 1) + M_{\text{uc}}(20 - Y_{\text{uc}} - 1) \]

\[ + N_{\text{bat}}C_{\text{bat}}(Y_{\text{bat}} + 1) + M_{\text{bat}}(20 - Y_{\text{bat}} - 1) \]

\[ + N_{\text{inv}}C_{\text{inv}}(Y_{\text{inv}} + 1) + M_{\text{inv}}(20 - Y_{\text{inv}} - 1) \]  

(2.2)

\[ F_{\text{space}} = N_{\text{uc}}S_{\text{uc}} + N_{\text{bat}}S_{\text{bat}} \]  

(2.3)

\[ F_{\text{weight}} = W_{\text{uc}}N_{\text{uc}} + W_{\text{bat}}N_{\text{bat}} \]  

(2.4)

\[ F_{\text{time}} = f_{\text{accel.time}}(N_{\text{uc}}) \]  

(2.5)

In (2.1) the multiple objective function distributed to four single objective functions, (2.2)-(2.5), which express cost, space, weight, and acceleration time functions, respectively.

There are two more parameters \( Y_{\text{uc}} \) and \( Y_{\text{bat}} \), which are the ratio of life time of the system over life time of the ultracapacitor and battery respectively. They show the number of replacements beyond the first period. \( f_{\text{accel.time}}(N_{\text{uc}}) \) is an inverse function of number of UC cells, as acceleration time varies inversely with the number of UC, \( N_{\text{uc}} \). The coefficients of space, weight, cost and acceleration time include the scaling factor. Values of the coefficients are chosen by manufactures and customer demands. In this work, recommendations of 85 customers have been collected and the coefficients have been chosen accordingly as \( k_{\text{weight}} = 7.5\% \), \( k_{\text{space}} = 20\% \), \( k_{\text{cost}} = 42.5\% \), and \( k_{\text{accel}} = 30\% \). These values are the average value of all participants in the survey. In addition, it also considered that in the worst case scenario the life spans of an electrified vehicle, battery and UC, and the inverter are 20 years, 3 years, 6 years and 5 years, respectively. By varying the coefficients, the objective function in (2.1) can be used to optimize the size of the energy system for any combination of the design factors, depending on the manufacturer specifications and design goals. In the proposed objective function, the factor of aging has been considered by using replacement and maintenance cost as mentioned in the nomenclature for (2.2) to (2.5) and it includes replacement and maintenance costs for both battery and UC. Also the effect of aging in energy density and
state of health of the system has been considered in the constraints which will be explained in section 2. Equation (2.1) also accommodates technical constraints of the optimization procedure which are stated in (2.6). Initially, the boundary equations for the energy sources involve the equality constraints, defined as (2.7). The DOD values of battery and UC have been chosen 0.7 and 0.9 respectively. The schematics of the proposed energy management system for three scenarios with/without regeneration in the vehicle are as shown in Figure 2.1a, b, and c. The three different scenarios considered in the investigations involving both battery and UC are as follows:

1) No regeneration for both UC and battery.
2) Charging and discharging of only the UC (regenerative braking energy for UC) is possible.
3) Charging and discharging for both battery and UC are possible (regenerative braking energy for both battery and ultracapacitor).

\[
\begin{align*}
SOC_{uc}^{(i)} &= \frac{P_{uc}^{(i)}}{P_{T,uc}} \\
S_{T,uc} &= P_{uc,cell}N_{uc} \\
SOC_{min,uc} < SOC_{uc}^{(i)} < 1 \\
SOC_{min,uc} &= 1 - DOD_{uc} \\
SOC_{bat}^{(i)} &= \frac{P_{bat}^{(i)}}{P_{T,bat}} \\
S_{T,bat} &= P_{bat,cell}N_{bat} \\
SOC_{min,bat} < SOC_{bat}^{(i)} < 1 \\
SOC_{min,bat} &= 1 - DOD_{bat} \\
\left[ P_{uc}^{(i)} + P_{bat}^{(i)} \right] \eta_{inv} &\geq P_{load}^{(i)}
\end{align*}
\] (2.6)

\[
\begin{align*}
P_{T,bat}^{max} &= N_{bat}P_{bat,cell}^{max} \eta_{inv} \\
P_{T,uc}^{max} &= N_{uc}P_{uc,cell}^{max} \eta_{inv} \\
P_{T,bat}^{min} &= P_{T,bat}^{max} DOD_{bat} \eta_{inv} \\
P_{T,uc}^{min} &= P_{T,uc}^{max} DOD_{uc} \eta_{inv}
\end{align*}
\] (2.7)

2.6 and 2.7 depict the constraints of both batteries and UCs state of charge (SOC). In each iteration of i, total power of UCs and batteries, and finally the reliability constraints which generating power should be greater than demanded power.
All parameters have been expressed in nomenclature at the beginning of the dissertation. The subscript \( t \) stands for Total. In all three scenarios, UC provides the high load rate of the system due to its high power specification and also its fast dynamics to provide high frequency loads and the battery delivers the base load, which is low frequency and meets the low dynamics of the battery and is consistent over the drive cycle.

### 2.2.1 Optimization without Regenerative Braking

In this scenario, no regenerative braking energy is available for storage in battery or UC. The battery supplies the base load and the UC supplies the peaking power needed for acceleration. When both battery and UC do not store the regenerative braking energy, the system is optimized with respect to the corresponding constraints mentioned in Figure 2.1a, b, and c. If the \( \text{SOC}_{uc,t} < \text{SOC}_{min,uc} \) or \( \text{SOC}_{bat,t} < \text{SOC}_{min,bat} \) then the \( N_{uc,i} \) and \( N_{bat,i} \) under consideration are ignored. Here the subscript \( t \) stands for the time and subscript \( i \) stand for the iteration of the optimization. In this case, there is no need to check \( P_{T,bat}^{\text{max}} \) and \( P_{T,uc}^{\text{max}} \), since no energy will be stored during the operation. However, the minimum SOC conditions of both the battery and the UC are checked at each time step.

### 2.2.2 Optimization with Regenerative Braking in UC

In this scenario, as shown in Figure 2.1.b regenerative braking energy can be stored in the UC. Thus, according to the demand profile, both battery and UC will supply the load but; when accelerating, UC will supply the extra demand. During deceleration of the vehicle, regenerative braking energy will be stored in the UC. The system in this scenario is optimized with respect to the corresponding constraints mentioned in Figure 2.1.b. The SOC of the UC is monitored for maximum and minimum boundaries, while the condition of battery is checked for minimum boundary in each step. So if

\[
P_{\text{load}}^{(i+1)} \leq P_{\text{load}}^{(i)}
\]

then
\[ P_{\text{uc}}^{(i+1)} = P_{\text{uc}}^{(i)} - \Delta P_{\text{load}}^{(i)} \Delta \eta_{\text{inv-rev}} \]  

(2.8)

and if \( P_{\text{load}}^{(i+1)} \geq P_{\text{load}}^{(i)} \) then \( \Delta P_{\text{load}}^{(i)} < 0 \),

\[ P_{\text{uc}}^{(i+1)} = \frac{P_{\text{uc}}^{(i)} - P_{\text{load,uc}}^{(i)}}{\eta_{\text{inv}}} \]  

(2.9)

\[ P_{\text{bat}}^{(i+1)} = \frac{P_{\text{bat}}^{(i)} - P_{\text{load,bat}}^{(i)}}{\eta_{\text{inv}}} \]  

(2.10)

The values of \( \eta_{\text{inv-rev}} \) and \( \eta_{\text{inv}} \) are usually considered to be 0.9 [20].

2.2.3 Optimization with Regenerative Braking in Battery and Ultracapacitor

In this scenario, the regenerative braking energy can be stored in both the battery and the UC. Here, the boundary conditions are checked for maximum and minimum values at each time step. The system is optimized with respect to the corresponding constraints mentioned in Figure 2.1a, b, and c. If the \( \text{SOC}_{\text{uc},t} < \text{SOC}_{\text{min,uc}} \) or \( \text{SOC}_{\text{bat},t} < \text{SOC}_{\text{min,bat}} \) then the failure in simulation for that solution will be considered.

\[ X_1: \text{number of bat} \quad X_2: \text{number of UC} \quad i=1 \]

Calculation of \( P_{\text{load}}^{(i)}, P_{\text{uc}}^{(i)}, P_{\text{bat}}^{(i)} \) No

Regenerative brake energy for UC

Yes

\[ P_{\text{bat}}^{(\text{min})} < P_{\text{bat}}^{(i)} \]

Yes

No

\[ P_{\text{uc}}^{(\text{min})} < P_{\text{uc}}^{(i)} \]

\[ \text{UC & bat discharge} \quad \text{Simulation failure} \]

\( i=1248 \) No

Yes

Simulation successful \( i = i+1 \) go to start Simulation failure

Figure 2.1a. Proposed optimal sizing based on EMS without regenerate brake energy.
Figure 2.1b. Proposed energy management algorithm with regenerate brake energy for UC.

\[ \begin{align*}
X_1: \text{number of bat} & \quad X_2: \text{number of UC} \\
& \quad i = 1 \\
\text{Calculation of } P^{(i)}_{\text{bat}}, P^{(i)}_{\text{uc}} \\
P^{(i)}_{\text{load}} < P^{(i)}_{\text{bat}} + P^{(i)}_{\text{uc}}\quad \text{No} \\
\text{Regenerative brake energy for UC} \\
P^{(i)} < P^{(i+1)} \quad \text{Yes} \\
P^{(i)}_{\text{uc}} < P^{(\text{max})}_{\text{uc}} \quad \text{No} \\
\text{UC charging} \\
P^{(i)} = P^{(\text{max})}_{\text{uc}} \quad \text{Yes} \\
\text{Battery discharging} \\
i = 1248 \quad \text{No} \\
\text{Simulation successful} \quad i = i + 1 \text{ go to start} \\
\text{Simulation failure} \\
\end{align*} \]

Figure 2.1c. Proposed energy management algorithm with regenerate brake energy for both battery and UC.

\[ \begin{align*}
X_1: \text{number of bat} & \quad X_2: \text{number of UC} \\
& \quad i = 1 \\
\text{Calculation of } P^{(i)}_{\text{bat}}, P^{(i)}_{\text{uc}} \\
P^{(i)}_{\text{load}} < P^{(i)}_{\text{bat}} + P^{(i)}_{\text{uc}}\quad \text{No} \\
\text{Regenerative brake energy for battery and UC} \\
P^{(i)}_{\text{load}} < P^{(i+1)}_{\text{load}} \quad \text{Yes} \\
P^{(\text{min})}_{\text{bat}} < P^{(i)}_{\text{bat}} < P^{(\text{max})}_{\text{bat}} \quad \text{No} \\
P^{(\text{min})}_{\text{uc}} < P^{(i)}_{\text{uc}} < P^{(\text{max})}_{\text{uc}} \quad \text{No} \\
\text{UC & bat charging} \\
P^{(i)}_{\text{bat}} < P^{(\text{max})}_{\text{bat}} \quad \text{Yes} \\
\text{UC & bat discharging} \\
i = 1248 \quad \text{No} \\
\text{Simulation successful} \quad i = i + 1 \text{ go to start} \\
\text{Simulation failure} \\
i = 1248 \quad \text{Yes} \\
\text{Simulation successful} \\
\text{Simulation failure} \\
\end{align*} \]
In scenarios 2 and 3, the proposed energy management scheme is based on the following equations:

If \( P_{load}^{(i+1)} \leq P_{load}^{(i)} \), then

\[
P_{uc}^{(i+1)} = P_{uc}^{(i)} - \Delta P_{load}^{(i)} \eta_{inv-rev}.
\]

\[
P_{bat}^{(i+1)} = P_{bat}^{(i)} - \Delta P_{load}^{(i)} \eta_{inv-rev} \cdot K_{bat}
\]

If \( P_{load}^{(i+1)} \geq P_{load}^{(i)} \), then:

\[
\eta_{inv-rev} = 0.6
\]

\[
K_{bat} = \frac{1}{3}
\]

\[
P_{uc}^{(i+1)} = \frac{P_{uc}^{(i)} - P_{load,uc}^{(i)}}{\eta_{inv}}
\]

\[
P_{bat}^{(i+1)} = \frac{P_{bat}^{(i)} - P_{load, bat}^{(i)}}{\eta_{inv}}
\]

where the battery co-efficient \( K_{bat} \leq 1 \) shows that the battery’s dynamics saves energy slower than the UC. Here this parameter has been considered as 1/3 experimentally.

2.3 Mathematical Modeling of the PSO Based Energy Management Scheme

2.3.1 Particle Swarm Optimization Scheme

The PSO algorithm is performed at each time step to determine if the calculated values of the variables meet the constraints. Subsequently, it is compared with the best result of the objective function \( P_{best} \) and the best among the entire swarm is stored as \( g \). Here the SOC parameters, UC model, battery model, and electric demand are the inputs to the optimization block. The PSO algorithm initializes and proceeds through the system flowchart according to each \( N_{uc} \) and \( N_{bat} \) which are the optimal number of the batteries and UCs the value of objective function is calculated during the simulation time.
According to the PSO algorithm the possible answers will be analyzed and the optimal value will be chosen from the possible answers.

According to Figure 2.4 in each time step, for each particle, the position is updated as follows [49]-[52].

$$x_{k+1}^i = x_k^i + v_{k+1}^i$$  \hspace{2cm} (2.17)

Each particle in PSO is associated with a pseudo velocity $$v_{k+1}^i (-v_{\text{max}}^i \leq v_{k+1}^i \leq v_{\text{max}}^i)$$, which represents the rate of change of position for the particle.

$$v_{k+1}^i = w_k v_k^i + c_1 r_{1,k} (p_{k}^i - x_k^i) + c_2 r_{2,k} (p_{k}^{\text{gi}} - x_k^i)$$  \hspace{2cm} (2.18)

Equation (2.18) is used to calculate each particle’s new $$N_{uc,i}$$ and $$N_{bat,i}$$ are ignored. Here the maximum SOC of UC and battery are also monitored to keep it less than 1.

Velocity $$v_{k+1}^i$$, based on its previous velocity $$v_k^i$$, and the distances of its current position, $$x_k^i$$ from its own best experience (position) and the best experienced position of its own informants, $$p_{k}^{\text{gi}}$$ according to Figure 2.2a will be updated. Here, subscripts indicate a pseudo time increment and the number of particles, respectively; $$r_1$$ and $$r_2$$ represent uniform random numbers between 0 and 1, which will be regenerated at each iteration. $$c_1$$ and $$c_2$$ normally are two positive constants, called the cognitive and social parameters, respectively, (in this study, they are time varying, $$c_{1\text{first}}=1.5$$, $$c_{1\text{end}}=2.5$$ and $$c_{2\text{first}}=2.5$$, $$c_{2\text{end}}=1.5$$ according to the best values in each iteration) [50]-[51]. The inertia weight, $$w_k$$ in (2.18) should neither be too large, which could result in premature convergence, nor too small, which may slow down the convergence excessively. They are chosen as $$w_{\text{min}}=0.6$$, $$w_{\text{max}}=1.2$$, holding the value at the beginning of each simulation cycle and increasing linearly until the end [52]. In this section, the information links between the particles that were defined once (and kept unchanged throughout the simulation), according to the “circular” diagram as shown in Figure 2.2b Each particle has a set of informants of fixed size, $$k$$. The neighborhood of size, $$k$$, of a particle is obtained from the virtual circle by recruiting alternately on the right and left of its position until a total of $$k$$ neighbors are obtained. The particle itself is also included, i.e., $$k=3$$. In this study, a swarm with 30 particles is used.
The termination of the optimization is the number of generations, which is chosen as 50. Based on the PSO algorithm the algorithm has been forced to converge to optimal values. The proposed Improved PSO algorithm converges to the optimal values of the fitness function over the defined iteration (generation) by updating the cognitive coefficients dynamically towards the best answers and subsequently, the pseudo velocity.

2.3.2 Optimized Energy Management System Applying PSO

\( N_{uc}^{i} \) and \( N_{bat}^{i} \) are selected as decision variables to be optimized. These variables are then computed using the equality constraint given in (2.7). To optimize the problem in each step, initial swarm needs to be defined, in PSO algorithm a random matrix will be defined to set the initial values of variables. (2.19)-(2.22) define swarm initialization:

\[
N_{uc,range} = I_{Population,T} \times (N_{uc,max} - N_{uc,min}) 
\]  
\[
N_{uc} = I_{Population,T} \times N_{uc,min} + Rand_{Population,S} \times N_{uc,range} 
\]  
\[
N_{bat,range} = I_{Population,T} \times N_{bat,max} - N_{bat,min} 
\]  
\[
N_{bat} = I_{Population,T} \times N_{bat,min} + Rand_{Population,S} \times N_{bat,range} 
\]

where \( N_{uc,max} \) and \( N_{bat,max} \) are the maximum allowable number of UCs and batteries respectively.

According to each \( N_{uc} \) and \( N_{bat} \), the value of \( P_{uc,t}^{(i)} \) and \( P_{bat,t}^{(i)} \) are calculated during the simulation time. According to the PSO algorithm the possible answers will be analyzed and the optimal value will be chosen from the possible answers.

2.4 Off-line Experimental Validation of The PSO-based Energy Management Scheme

Experiments were performed on an in-house EV equipped with necessary data acquisition systems as shown in Figure 2.3 to capture data from road test, which was then used to determine off-line, the optimized size of battery/UC combination for the particular load profile of the EV. The EV was driven by a 5.69 kW aluminum-rotor induction motor powered by a battery pack. The data captured from the road test is given
in Figure 2.5 [53]. The load demand profile obtained from the electric vehicle under urban driving tests comprising multiple instances of acceleration and braking is used as input to both the un-optimized and developed PSO based energy management systems assuming that the EV was powered by a battery/UC combination for the investigations performed here. The experimental results have been captured over a drive cycle for 1248 seconds which is a 5 repeat of 250 seconds actual drive cycle. Since the driving cycle data is the optimization input, any drive cycle can be utilized for the optimization program. Thereafter, the proposed optimized PSO based energy management strategy has been compared with an un-optimized based energy management system in this section to bring out the merits of the developed scheme. Moreover, the optimized scheme has been validated through sensitivity analysis. The components used in this study are tabulated in Table 2-1. Therefore all results in Table 2-2 to Table 2-4 are based on these ratings and specifications.

<table>
<thead>
<tr>
<th>TABLE 2-1. LI-ION BATTERY AND UC CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-ion Battery: A123 systems</td>
</tr>
<tr>
<td>Cell cost</td>
</tr>
<tr>
<td>Cell volume</td>
</tr>
<tr>
<td>Cell weight</td>
</tr>
<tr>
<td>Life time</td>
</tr>
<tr>
<td>Maintenance cost</td>
</tr>
<tr>
<td>Cell Energy</td>
</tr>
</tbody>
</table>

Figure 2.2. Particles updating and circular behavior. (a) Three fundamental elements the particles position updating. (b) Graph of influence of a swarm of N particles in circular form with three informants for each particle.
2.5 Un-optimized Energy Management System

The Wavelet transform is chosen to facilitate energy management for the un-optimized case. The Wavelet transform has proven its usefulness in the analysis of various types of signals, and has recently been applied to a variety of applications [54], [55]. Haar filtering with one level of decomposition is used. Haar filter is well-known filter with industrial application especially in EMS. Since UC as the only fast dynamics electric source is generating the high frequency part of the drive-cycle, one level of filtering in wavelet transform is enough to get the battery and UC shares of the power. This technique is a reliable tool for energy management, presenting an opportunity for comparison with the proposed optimized algorithm.
2.6 Optimized Energy Management System

While implementing the PSO algorithm, the initial values used for the objective functions are assigned by intuition (best guess). The possible optimal answer will then be selected and the swarms’ positions will be updated, for each decision variable according to (2.20) and (2.22). The following inequality constraints are applied to modify the swarms’ positions.

If $P_{uc}^{(i)} \leq P_{uc}^{\text{min}}$ then the simulation failed.

If $P_{uc}^{(i)} \geq P_{uc}^{\text{max}}$ then $P_{uc}^{(i)} = P_{uc}^{\text{max}}$

If $P_{bat}^{(i)} \leq P_{bat}^{\text{min}}$ then the simulation failed.

If $P_{bat}^{(i)} \geq P_{bat}^{\text{max}}$ then $P_{bat}^{(i)} = P_{bat}^{\text{max}}$
The above inequality constraints ensure that improper selections for $N_{uc}$ and $N_{bat}$ are adjusted into the space of appropriate dispatch assignments. The PSO algorithm is illustrated in accordance to each $N_{uc}$ and $N_{bat}$, the value of $P_{uc}^{i}$ and $P_{bat}^{i}$ are calculated during the simulation time. According to the PSO algorithm, the possible answers will be analyzed and the optimal value will be chosen from the possible answers. For the initial searching points, 30 swarms and 50 iterations are used.

2.6.1 PSO Based Optimized EMS Considering No Regenerative Braking Energy Storage

Figure 2.6a. shows the convergence of the PSO optimization algorithm for five different multiple objective functions (objective function including cost, space, weight, and acceleration time or any combination with three of them). It can be seen that for all
cases, the fitness function converges to the optimal answer within 50 iterations. Figure 2.6b. shows the SOC of the battery for these 5 different cases. As can be seen, for all states, the battery SOC remains above the minimum allowable value until the end of the desired time. Figure 2.6c. shows the SOC of UC for these five differently obtained urban test runs. In all states, the UC SOC remains above the minimum allowable value.

(a)

(b)
Figure 2.6. No regenerative braking scenario. A) Convergence diagram. b) Battery SOC. c) UC SOC.

### 2.6.2 PSO Optimized Hybrid System Considering Regenerative Braking Energy Can Be Stored in UC

The convergence of the PSO optimization algorithm, battery SOC and UC SOC is presented in Figure 2.7a. In this scenario, during the deceleration period, the UC SOC can increase because of the regeneration brake energy.
Figure 2. Scenario of regenerative braking energy stored in UC. a) Convergence diagram. b) Battery SOC. c) UC SOC.

2.6.3  **PSO Optimized Hybrid System Considering Regenerative Braking Energy for both Battery and UC**

Figure 2.8a, b, and c show the PSO for this algorithm, battery SOC and UC SOC, respectively. During the deceleration period, the battery and UC state of charge (SOC) can increase as the regenerative braking energy is considered for both battery and UC. According to un-optimized wavelet EMS the numbers of batteries and UCs calculated as 55 and 14 respectively. The results are based on meeting the demands due to the load and also no regenerative braking energy is available.
Table 2-2 shows the optimization based on PSO considering no regenerative braking energy. This method was applied to all 5 cases of multiple objective functions. Table 2-3 is regarding the optimization based on PSO considering regenerative braking energy stored in UC. This method was also applied to all five cases of multiple objective functions. As it can be seen for all cases there is a difference in numbers of sizing. Therefore, batteries and UCs used will be less number in this scenario. Finally, Table 2-4 shows the optimization based on PSO considering regenerative braking energy stored in both UC and battery. Number of batteries and UCs used in this scenario will be less in numbers as compared to the previous ones according to regenerative energy for both battery and UC. In Figures 2.9 and 2.10 the sensitivity analysis of the optimization result is shown. Figure 2.9 shows the analysis of the scenario of regenerative braking energy stored in the battery and UC. It can be seen that any value around the optimal value, \(N_{bat}=19\) more or less, yields a poor result in comparison to the optimal value.

(a)
Figure 2.8. Scenario of regenerative braking energy stored in both UC and battery. a) Convergence diagram. b) Battery SOC. c) UC SOC.

### Table 2-2.

**OPTIMIZED RESULT WITH NO REGENERATIVE BRAKING ENERGY**

<table>
<thead>
<tr>
<th>Method 1: No regen braking energy</th>
<th>Battery number</th>
<th>UC Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$(weight, space, cost, acceleration time)</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>$F$(weight, space, acceleration time)</td>
<td>39</td>
<td>12</td>
</tr>
<tr>
<td>$F$(weight, cost, acceleration time)</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>$F$(space, cost, acceleration time)</td>
<td>37</td>
<td>10</td>
</tr>
<tr>
<td>$F$(weight, space, cost)</td>
<td>38</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table 2-3.

**OPTIMIZED RESULT WITH REGENERATIVE BRAKING ENERGY IN UC**

<table>
<thead>
<tr>
<th>Method 2: Regen braking energy for UC</th>
<th>Battery number</th>
<th>UC Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$(weight, space, cost, acceleration time)</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>$F$(weight, space, acceleration time)</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>$F$(weight, cost, acceleration time)</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>$F$(space, cost, acceleration time)</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>$F$(weight, space, cost)</td>
<td>30</td>
<td>7</td>
</tr>
</tbody>
</table>
It is obtained from the tables 2-2 to 2-4 that using the regenerate brake energy for both battery and UC can result on lower number of battery and UC cell and lower cost as a result. Also looking at each table itself depicts that the weighting factor of each single objective function can effect in the optimal results, for example in table 2-3 if we ignore acceleration time, the number of UC decrease compare to other states and it is because of this fact that UC is in charge of acceleration in EV. The same purpose of the regenerative braking energy stored in UC shown in Figure 2.10. The purpose of the sensitivity analysis is to confirm the results of the proposed energy management using PSO methodology. According to this sensitivity analysis, the local optimum objective function value is the one that the proposed EMS algorithm, has found.

Lemma1;

If the hessian matrix of a function is PSD (Positive semi definite), the function is convex [56].

Figure 2.9. Sensitivity analysis for scenario of regenerative braking energy stored in battery & UC - $F$(weight, space, cost, acceleration time).

Figure 2.10. Sensitivity analysis for scenario of regenerative braking energy stored in battery and UC - $F$(weight, space, cost, acceleration time.)

Table 2-4.

<table>
<thead>
<tr>
<th>Method 3: Regenerative braking energy for UC &amp; battery</th>
<th>Battery Number</th>
<th>UC Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$(weight, space, cost, acceleration time)</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>$F$(weight, space, acceleration time)</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>$F$(weight, cost, acceleration time)</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>$F$(space, cost, acceleration time)</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>$F$(weight, space, cost)</td>
<td>19</td>
<td>7</td>
</tr>
</tbody>
</table>
Lemma 2;

For a convex function, the local optimal value is the global optimum value. Based on lemma 1, the proposed objective function of the hessian matrix which includes two variables, \( N_{bat} \) and \( N_{UC} \), if simply \( f_{uc} = k/x \) are:

\[
\begin{bmatrix}
\frac{d^2 f}{dx_1^2} & \frac{d^2 f}{dx_1 dx_2} \\
\frac{d^2 f}{dx_2 dx_1} & \frac{d^2 f}{dx_2^2}
\end{bmatrix} \geq 0
\]  \hspace{1cm} (2.23)

\[
\begin{bmatrix}
0 & 0 \\
0 & K/ N_{UC}^3
\end{bmatrix} \geq 0
\]  \hspace{1cm} (2.24)

where \( K \) and \( N_{UC} \) are positive definite.

Using the sensitivity analysis demonstrates that the results are locally optimal. Therefore based on lemma 1 and 2, the optimal values of the proposed scenarios are global optimum values. To verify the accuracy and pace of the proposed PSO based energy management strategy in this paper, GAMS solvers were applied. The main advantage of GAMS is letting users encode the model and run it via several available solvers that handle different types of models. The fastest results achieved from GAMS were DICOPT solver with a calculation time of 9 seconds for the regenerative brake energy of the UC- scenario 2. Table 2-5 shows that all the scenarios of PSO based EMS take no more than 3.5 seconds. DICOPT, the solver that is used to solve MINLP (Mixed-Integer Nonlinear Programming) model in this paper, is a powerful solver using CPLEX solver for linear sub-models and CONOPT solver for nonlinear sub-models. Having the ability to handle large volume of input data in order to solve large models in a short time, CPLEX is the most powerful solver for linear programming and mixed integer linear
programming, and has been used in mathematical programming researches all over the world. CONOPT has the same capability to handle large models in NLP models as CPLEX has in MILP models.

2.7 Validation of Proposed Optimal Sizing in Vehicle Simulator

The proposed EMS based on IPSO algorithm is validated in vehicle simulator software considering regenerative braking for battery and UC. Figure 2.11 shows the required power demand for one US06 drive cycle based on which the ESS is sized in the vehicle model. The components of the vehicle have been sized according to the net propulsive force required. Two cycles of US06 drive cycle are chosen as the total required range of the vehicle. An optimally sized ESS based on the IPSO algorithm is used as the source of energy and both battery and ultracapacitor are capable of gaining regenerative braking energy. Figure 2.12 and Figure 2.13 show output power from battery and ultracapacitor and SOC of battery and ultracapacitor respectively, for one drive cycle. In Figure 2.13, it can be seen that the SOC of battery and UC do not fall below or exceed the specified range.

2.8 Online Application of Proposed EMS Using Real-time Simulator (RT-Lab)

In order to verify the accuracy and to prove the effectiveness of the proposed EMS based on IPSO, a real-time simulation of the model has been performed using Opal-RT system. Figure 2.14 depicts the system outline of real-time verification. To achieve the experimental verification, according to Figure 2.14, the motor (A) load in each second should be sampled and transferred into the real-time simulator through its I/O input card (B); the EMS developed (C, D, E) sends appropriate control signals to the DC/DC converter (G) and then ESS (H) through I/O output card (F). The real-time simulator includes master (C) for compilation of the proposed EMS algorithm (D) and a console (E) which is an interface between the input and output cards with master. The ESS sizing results in the selected EMS closely following the obtained results from IPSO optimization.
Figure 2.11. Power demand in one US06 drive cycle.

Figure 2.12. Battery and ultracapacitor output power for one US06 drive cycle.

Figure 2.13. SOC of battery and ultracapacitor for one US06 drive cycle.
In this study, electric motor, battery, ultracapacitor and DC/DC converter have been modeled in Matlab to depict software-in-the-loop type of simulation [57]. Therefore the demanded power of the simulated motor will be sent out using the I/O card of Opal-RT and will be transferred to proposed EMS model based on IPSO optimization using the I/O card as input. There are three different EMS scenarios, as explained in the previous sections, but for verification, case II has been used. The control signal out of this EMS will be sent out to the DC/DC converter model using I/O card of Opal-RT real time simulator. According to the results of this test bench, the proposed EMS strategies which has been used in real-time.

The proposed EMS is fast and proper to be applied in EV system and the results of optimal sizing, which has been considered as the design parameters in this modelling, depicts the accuracy of the IPSO algorithm used here. Figure 2.15 depicts that

Figure 2.14. Online application of proposed EMS using real-time simulator (RT-Lab).

Figure 2.15. Battery and Ultracapacitor SOC tested by Real-time simulator (opal-RT).
the battery and Ultracapacitor SOC never go down the predetermined minimum SOC and closely follows the results shown in Figure 2.8. The proposed IPSO optimal sizing as mentioned earlier can be using as an online application in EMS system, but in this case the objective function is to find the best values of the wavelet EMS or any other filtered base EMS coefficients to achieve the best results. Since IPSO is fast enough, it is recommended to be applied in online EMS system of EVs.

2.9 Conclusion

A hybrid energy source of battery/UC has been used here to supply a commercially available electric vehicle. According to the four different scenarios, which have been considered, the optimized and un-optimized results of sizing hybrid energy sources were illustrated. It is found that the three proposed optimized scenarios yield better results than the un-optimized wavelet EMS. Also, the scenario of the regenerating braking energy for battery and UC has the best results. To summarize, the developed EMS promotes energy sustainability in two ways: 1) by ensuring an optimal sizing of hybrid energy sources based on multiple constraints; and 2) by incorporating a multiple objectives function into the EMS’s decision-making process. Specifically, the following factors are considered.

1. The use of a regenerative braking energy to increase the energy efficiency of the system.
2. Keeping the whole aspect of the optimization with the importance factor determined by the manufacturers
3. A high reliability by keeping the SOC of the battery and UC higher than 20%, which can be determined by designer in any other values.
Chapter 3

Short Term Power Demand Forecasting in Light- and Heavy-duty Electric Vehicles through a Linear Prediction Method

3.1 Introduction

The extreme need of the market on EV/HEV products especially in public transportation and also light duty vehicles caused a fast rate of developing in EV/HEV technology and their EMS systems. Considering both heavy and light duty, the efficiency of these vehicles can be enhanced by assisting the energy management system with preemptive knowledge of power demand, which can lead to effective and efficient utilization of the vehicle’s powertrain. The prediction scheme proposed in this paper assists the energy management system by forecasting the load demand based on frequently updated history of the vehicle. Using the knowledge of traffic ahead, the EMS in the vehicle can react to changes in traffic density or speed before they happen, enhancing the response time of various components and hence the efficiency of a trip. Background literature obtained from [1]-[3] illustrates that the EMS of electric (EV) and hybrid electric vehicles (HEV’s) require prediction times in the range of seconds ahead of interest as the problems associated with delay due to vehicle dynamics have to be dealt with. Thus, short-term demand prediction can be used as a tool towards improved dynamic control of these vehicles by making short-term decisions. The short-term decisions could be either changing from one power source to the other in a HEV, or changing the power flow among the different hybrid sources in an electric vehicle and/or any other control action, which involves delays.
3.2 Modeling and Analysis of the Developed Linear Prediction Technique for Light and Heavy Duty Electric Vehicles

3.2.1 The Linear Prediction Method

Linear prediction method is a powerful technique for predicting a time series in a time-varying environment. A power demand profile of light or heavy-duty vehicle typically belongs to a time-varying process. The linear prediction model, recursively represents the time series of signal samples over a time interval [4], as in (3.1).

\[
y(t + T) = a_1 y(t) + a_2 y(t - T) + \ldots + a_m y(t - (m-1)T) \\
+ b_1 u(t + T) + b_2 u(t) + \ldots + b_n u(t - nT) + c_1 e(t)
\]  

(3.1)

Here \(a_1, a_2, \ldots, a_m, b_1, \ldots, b_n,\) and \(c_1\) are the model coefficients, ‘\(m\)’ is the model degree, \(y(t+T)\) is the future sample, \(y(t)\) the present observation, \(y(t-T)\) and \(y(t-nT)\) are the immediate and n\text{th} past observations, respectively, \(u(t)\) and \(u(t-T)\) are the present and immediate past inputs, respectively, and \(e(t)\) is the present model error. In (3.1), if \(a_1 = \ldots = a_m = 0\), the model is called moving average or an all-zero model (if considered as a transfer function). If \(m>1\) and \(b_1 = \ldots = b_n = 0\), the model is called an auto-regressive or an all-pole model. If \(m>1\) and \(n>1\), the model is called ARMA (auto-regressive moving average) or the pole-zero model [58].

After modeling each window the sampler advances by one step, thus, updating the model for the new data window. Parametric models for short term demanded power prediction are often based on (3.1), which is mostly a recursive process and predicts the demanded power at time \(t+T\). However, if more time steps are required, then the process may be recessively employed [59]. If \(b_1 = \ldots = b_n = 0\) and \(e(t)\) is ignored then (3.1) can be written as in (3.2).

\[
y(t + T) = a_1 y(t) + a_2 y(t - T) + \ldots + a_m y(t - (m-1)T)
\]  

(3.2)

The output is the linear combination of the present and past samples; hence the name, linear prediction. Two steps are required for short term demanded power prediction using (3.2).
In this application $y(t)$ is the demand of EV which should be predicted and there is no input here i.e. $x(t)$. Referring to (3.2), the model degree ($m$) must be carefully selected and the coefficients, $a_1, ..., a_m$, must be calculated from the modeling window. The model can be used to predict the demanded power for the time steps ahead. The idea of the short term demanded power prediction is represented in Figure 3.1 [60]. Primarily, the modeling window is used to find the best model for the waveform meanwhile the model parameters are used to predict the demanded power in the future.

### 3.2.2 Estimating the Coefficients of the Linear Prediction Model

If the modeling error is considered, (3.2) can be rewritten as in (3.3). In order to estimate the coefficients $a_1, a_2, ..., a_m$ in (3), the least squares error method will be used. This error is between the estimated value, at time $t'$, and the measured value, at that same instant.

$$y(t+T) = a_1y(t) + a_2y(t-T) + ... + a_m y(t-(m-1)T) + e(t)$$  \hspace{1cm} (3.3)

In the least squares error method, the energy in the error signal is minimized. It should be mentioned that the error is generated because the linear prediction model cannot be fitted with zero error to the actual signal. A set of equations as presented in (3.4) is used to find the coefficients, $a_1, ..., a_m$, [61].

$$[Y] = [\phi] [A] + [E]$$  \hspace{1cm} (3.4)
where:

\[
[Y] = \begin{bmatrix} y(t) & y(t-T) & \cdots & y(t-kT) \end{bmatrix}^T
\]

\[
\phi = \begin{bmatrix} y(t-T) & y(t-2T) & \cdots & y(t-mT) \\ y(t-2T) & \cdots & \cdots & \cdots \\ \vdots \\ y[t-(k+1)T] & \cdots & \cdots & y(t-(m+k)T) \end{bmatrix}
\]

\[
A = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix}, \quad E = \begin{bmatrix} e(t) \\ e(t-T) \\ \vdots \\ e(t-kT) \end{bmatrix}
\]

Elements in vector \( A \), are the coefficients that can be found by the least squares error method as follow:

\[
\]  \hspace{1cm} (3.5)

In this methodology if \( m \) is chosen greater than the required value, (3.5) cannot be solved for any unique set of coefficients because some columns in matrix \( \phi \) are not independent of each other. Hence \( \phi^T \phi \) would be singular and will not have an inverse. This means the system of equations in (3.3) will have an infinite number of answers for the coefficients. Also, if \( m \) is chosen less than the required value, the number of independent equations would be more than the number of un-known variables \( (a_1, \ldots, a_m) \). Such a system of equations must be solved for the best approximation of coefficients.

The best approximation for the coefficients \( (a_1, \ldots, a_m) \) is to use the least squares error method. Generally, the least squares method is the most effective modeling process used in practice with demanded power signals. The best modeling order, \( m \), is suggested to be the smallest possible value which provides sufficient and acceptable results based on the standard error in prediction area. The best modeling window is the smallest window that gives acceptable results [61].
3.2.3 Experimental Data Acquisition of Light and Heavy Duty Electric Vehicles Used in the Investigations

Section 3 of this chapter illustrates the measured results obtained from an on-road vehicle test performed using the laboratory light duty electric vehicle. The electric car uses a 7.5 hp aluminum-rotor induction motor with a variable frequency drive. The vehicle instrumentation layout is as shown in Figure 3-2. Also, the power demand profile of the heavy duty electric vehicle obtained from urban dynamometer driving cycle of an electric bus as given in the Autonomy software is as shown in section 3.3. The maximum speed achieved by the bus was 56 miles/hour and acceleration/deceleration was 1.47 mile/sec². The power demand profile of the electric bus was found to vary slowly when compared to that of the car.

Hence, it can be inferred from this study that, as the load increases, acceleration has to be increased in order to keep up the constant speed of the vehicles. In the process of accelerating, the power demand has to meet by the power sources. Using the linear prediction method proposed in the paper, the power demand can be estimated beforehand and the energy sources can be used effectively, thus improving the efficiency of the vehicle [58].

Figure 3.2. Vehicle instrumentation layout. Data acquisition and logging notebook – A. Fluke 434 Power Quality Analyser – B. Tektronix TPS2024 digital storage oscilloscope – C.
Figure 3.3. Proposed linear prediction method output for light duty electric vehicle without filtering, with window length of 30 and lagging samples of 3.

Figure 3.4. Proposed linear prediction method output for heavy duty electric vehicle with window length of 30 and lagging samples of 3.

Figure 3.5. Filtered and non-filtered measured power demand profile.

Figure 3.6. Proposed linear prediction method output for light duty electric vehicle with filtering, with window length of 30 and lagging samples of 3.
3.3 Validation of the Proposed Linear Prediction Method for Light and Heavy Duty Electric Vehicles

3.3.1 Power Demand Forecast without Filtering the Measured Power Demand Waveforms

To predict the demanded power based on the linear prediction modeling of demanded power samples, equation (3.2) has been used. The results of applying the proposed method to the non-filtered demand power signal of the light and heavy duty electric vehicles are shown in Figures 3.3 and 3-4. These results are used for in a prediction time of 1 s, based on 30 samples for window length and for a model degree of \( m=3 \), which lead to good prediction including the sufficient history of data. The linear prediction method result for the light electric vehicle has quicker transitions in comparison to that of the heavy duty vehicle as dictated by the load profile of the respective vehicles. It can be seen that there is a small mismatch between the predicted and measured results for the light duty electric vehicle, which is acceptable as the correlation is 80%. Whereas, the predicted profile for the heavy duty electric vehicle is in closer agreement with that of the measured power and the correlation is found to be 97%. Thus, it was found that the prediction could be improved by filtering the load profile of the light duty vehicle, whereas the heavy duty load profile did not call for filtering because of the vehicle’s slower transition and satisfactory prediction. Hence the power demand forecast after filtering the light duty vehicle’s load profile is provided in Figure 3.5 [58].

3.3.2 Power Demand Forecast after Filtering the Measured Power Demand Waveforms

As was mentioned in the previous sub-section, filtering out ineffective frequency components for the spectrum of a signal can provide better prediction. The measured power is then filtered and sent to the predictive controller [62]-[64]. A low-pass filter is also imposed by the electric vehicle mechanical system. Filtering makes the measured power smoother and hence more predictable for short term. A sample real measured power is shown in Figure 3.5 along with its filtered measured power signal. The filtered
waveform together with the prediction results for one step (1 s) ahead, are plotted in Fig. 6. As shown in Figure 3.6, the linear prediction model gives acceptable result in the prediction standards. The linear prediction model is effective for a wide range of prediction times ahead and gives acceptable results. In Figure 3.6, the model degree is \( m = 3 \), the window length is five times ‘\( m \)’ (15 points with 1 s sampling period) and the prediction time is 1 s ahead. The correlation coefficient is detailed in Appendix A. Filtering the signal of the power demand, which keeps the trend of the signal and includes the whole signal sags and swells, was found to result in a correlation of more than 89%.

3.3.3- Illustration of the proposed Prediction Scheme through Haar Wavelet based Energy Management System

In order to validate and analyse the performance of the developed linear prediction scheme the predicted load profiles of the light duty and heavy duty electric vehicles were fed into a developed Haar wavelet based energy management system (EMS). The EMS was designed for two contemporary hybrid energy sources such as the battery and the ultracapacitor (UC), where the battery would serve the base load and the UC would assist peaking power demand in the vehicles because of their highly dynamic response. The predicted waveforms when fed into the EMS get assigned to either the battery or the UC based on the frequency of the samples. As shown in Figures 3.7 and 3-8, the high frequency components of the predicted power demand is assigned to the UC as they are periods peaking loads. On the other hand, the lower frequency components which represent the base load of the vehicles is assigned to the battery [58].
3.4 Modeling and Analysis of the Developed Optimized Linear Prediction Technique for Light and Heavy Duty Electric Vehicles

As it was explained in previous section, both the model degree and the window length will affect the prediction results. The way they affect the result can be critical and the error can vary greatly based on these two parameters. Therefore, the need of an optimized version of linear prediction is sensing in this problem [58].
Figures 3.9 and 3-10 depict the dependability of the prediction results on these two parameters. Figure 3.9 shows the three different error indices of the prediction results with changing of the length of the model.

As it can be seen all three indexes including Maximum Error (ME), Mean Absolute Percentage Error (MAPE), and Mean Square Error (MSE) show that the error of prediction varies with the length of the model and there is an optimal value at which the error is minimum [65].

Figure 10 depicts the effect of model order on the results of the prediction. It can be seen that all error indexes vary based on the value of model order. Finding the optimal value of the model order with fixed model length is not complicated but since both of them have their own effect on the results independently, then usage of an intelligent optimization as a proper tool for finding the optimal values of both model length and order can help effectively
The Optimized Linear Prediction Method

Since an optimized linear prediction to get the optimal prediction is required and to improve the prediction results significantly, a PSO optimization algorithm has been developed to improve the linear prediction algorithm. PSO has been explained in previous section and all the merits of this algorithm well expressed comprehensively there. In brief it is noted that, PSO is a fast and simple intelligent algorithm that can optimize any linear or nonlinear objective function mostly globally.

The speed of the algorithm is really important in the prediction based controller, since the algorithm will be used repeatedly with updated model data and needs to be converged fast to improve the system dynamics.

Figure 3.11 depicts the algorithm of the PSO based linear prediction, which will be an iterative algorithm with fast convergence time. The same PSO algorithm with section 3.3 algorithm has been used here. Therefore, the same Improved PSO (IPSO) optimization has been applied for modifying the linear prediction algorithm.
In the proposed IPSO, the cognitive coefficients $C_1$ and $C_2$ have been considered dynamically changing and also the number of the population considered more than regular PSO algorithm to increase the speed of the convergence since it can cover more samples of feasible space in each iteration [58].

### 3.4.2 Estimating the Coefficients of Optimized Linear Prediction Model

In order to get the optimized linear prediction model, the objective function for any of the error indexes should be defined. In each iteration, using of the IPSO population the prediction will be run and the best error will be kept as the minimum value of the objective function. Using the cognitive values and speed formulation of PSO next iteration will be generated and the new population will be used to run the linear prediction. This process will iteratively continue till the optimization converges to the optimal value. This optimization process is fast enough to be used as the prediction based controller in the electrified vehicle application.
3.5 Modeling and Analysis of the Developed Markov-Chain Based Linear Prediction Technique for Light and Heavy Duty Electric Vehicles

Markov chains are stochastic processes that can be parameterized by empirically estimating transition probabilities between discrete states in the observed systems [66]. Markov chain order represents the number of time steps (data) in the past that influence the probability of the distribution of the present state, i.e. the present state can be a combination of the number of past data probability in which the sum of all probability should be 1. For instance, a first order Markov chain means each subsequent state depends only on the immediate past state. Second, third and higher order Markov chains are chains that the next state depends on two, three, or more preceding data.

Consider \( X(t) \) as a stochastic process which possess a discrete state space \( S = \{1, 2, \ldots, K \} \). Then, for a determined sequence of time \( t_1 < t_2 < \cdots < t_{n-1} < t_n \), the conditional probabilities will be [66]:

\[
\Pr(X(t_n) = [i_1, \cdots, X(t_{n-1}) = i_{n-1}] = \Pr(X(t_n) = i_n \mid X(t_{n-1}) = i_{n-1}) \tag{3.6}
\]

The conditional probabilities \( \Pr [X(t_n) = i_n \mid X(s) = i] = P_{ij}(s,t) \) are called transition probabilities of order \( r = t-s \) from state \( i \) to state \( j \) for all indices \( 0 \leq s < t \), while \( 1 \leq i \) and \( j \leq k \). They are denoted as the transition matrix \( P \). For \( k \) states, the first-order transition matrix \( P \) has a size of \( k \times k \) and takes the form [66]:

\[
P_{\text{transition}} = \begin{bmatrix}
P_{1,1} & P_{1,2} & \cdots & P_{1,k} \\
P_{2,1} & P_{2,2} & \cdots & P_{2,k} \\
\vdots & \vdots & \ddots & \vdots \\
P_{k,1} & P_{k,2} & \cdots & P_{k,k}
\end{bmatrix} \tag{3.7}
\]

The probabilities of each state at time \( t \) will be calculated based on the number of the transitions from previous states to that states i.e. if \( n_{ij} \) is the number of transitions from state \( i \) to state \( j \) in the load demand data, the probability of this element of transition matrix will be estimated as:
Third-Order Transition Matrix Formation

At first, the demanded power data time series should be converted to demanded power states. This contains demanded power values between a known ranges of values. In [66] wind speed states were determined based on the average $V$ and standard deviation $S_v$ of the available wind speed data. In [67] the wind speed states have been determined based on an upper and lower limit with the step of 1 m/s for wind speed.

In this study the categorization of the states has been done based on the demanded power upper and lower limit, for example for an electrified vehicle whose its motor is a 100 kW AC motor, the states range can be 1 kW in which the number of states results in 100.

Based on state matrix, it is possible to find the number of transition from three past states, for third-order transition matrix, in demanded power data to another state at time $t+mT$. Therefore, the transition probabilities are calculated as expressed in 3.8.

For this study application, which is the electrified vehicle demanded power, the third-order autocorrelation coefficients are working properly comparing to the first and second order autocorrelation coefficients. But to generate the third order transition matrix with number of states of 100, the calculating time will be greater that second order Markov chain, and time wise, it is important to select the second order Markov chain to improve the linear prediction algorithm.
It is obvious that, higher accuracy can be expected by third-order Markov chain. Third-order transition probability matrix for \( k \) state is calculating as:

\[
\begin{bmatrix}
P_{1,1,1,1} & P_{1,1,1,2} & \cdots & P_{1,1,1,k} \\
\vdots & \vdots & \ddots & \vdots \\
P_{1,1,k,1} & P_{1,1,k,2} & \cdots & P_{1,1,k,k} \\
P_{1,2,1,1} & P_{1,2,1,2} & \cdots & P_{1,2,1,k} \\
\vdots & \vdots & \ddots & \vdots \\
P_{1,k,k,1} & P_{1,k,k,2} & \cdots & P_{1,k,k,k} \\
P_{2,1,1,1} & P_{2,1,1,2} & \cdots & P_{2,1,1,k} \\
\vdots & \vdots & \ddots & \vdots \\
P_{k,k,k,1} & P_{k,k,k,2} & \cdots & P_{k,k,k,k}
\end{bmatrix}
\] (3.11)

Here, the probability \( p_{ij,k,l} \) is the probability of the next demanded power in state \( l \) if the current demanded power state is \( k \) and the previous demanded power states were \( j \) and \( i \). This matrix has a size of \( k^3 \times k \). This shows how the probability of a transition depends on the current state and on the three preceding states.

In this study a second order Markov chain is used to modify the linear prediction which results in using of a nonlinear filter as depicted in Figure 3.12.

In this algorithm, the short-term patterns of demanded power data is obtained by linear prediction algorithm and the long-term pattern is obtained by second-order Markov chain.

![Figure 3.12. Proposed hybrid algorithm of Markov chain based linear prediction.](image-url)
Markov transition probability matrix is calculated as explained before from the power data and is used to modify the predicted values. This process is distributed into three sections as depicted in Figure 3-12. First, the transition probability matrix is formed using the second order Markov chain within a determined range of data of demanded power. Then, the short-term values will be calculated for remaining data of demanded power by using a linear prediction method. Eventually, probabilities for predicted values are calculated by using second-order Markov chain. Finally, modified prediction will be provided by a nonlinear filter, which improves the primary results based on the probability values from Markov chain transition matrix.

In order to modify the primary prediction values using the Markov transition probability matrix, a nonlinear filter has been applied. The nonlinear filter has been modeled as follows [68]:

\[
p_{t+T}^{\text{improved}} = \beta \left[ \alpha \cdot p_{t}^{\text{improved}} - (1 - \alpha) \cdot \text{power}_{t} \right] + (1 - \beta) \cdot p_{t+T}^{\text{linear}} \quad (3.12)
\]

where \( p_{t}^{\text{improved}} \) is the latest modified predicted value using (3.12), which is the proposed filter based on the prediction time, \( T \), and \( p_{t+T}^{\text{linear}} \) is the next predicted value based on prediction time, \( T \). Also \( \text{power}_{t} \) is the latest real value of demanded power, and \( \beta \) is the probability value for the primary prediction, which is the linear prediction, \( p_{t+T}^{\text{linear}} \), and will be calculated using Markov transition probability matrix. Here \( \alpha \) is a parameter in the nonlinear filter to record the historical performance of the model, which is varying between 0 and 1. The more accurate the past predictions are, the smaller this parameter should be. The value of \( \alpha \) is calculated in each prediction iteration using (3.13):

\[
\alpha = \frac{p_{t}^{\text{improved}} - \text{power}_{t}}{\text{power}_{t}} \quad (3.13)
\]

Applying the filter in (3.12), the primary (linear) prediction, which is considered as unreliable prediction to be replaced by a weighted previous demanded power data and the current prediction for the future based on prediction time. Also, the nonlinear filter performs weighted averaging process.
The results show that the proposed algorithm results better than the traditional linear prediction method. The MPE and MAPE are decreased significantly in the Markov-chain based linear prediction algorithm. With existence of the significant fluctuation in demanded power data, the accuracy of proposed algorithm is extremely good. Error (MAPE) is used to measure the performance of the proposed prediction algorithm. It is defined as follow:

\[
MAPE = \frac{1}{n} \sum_{t=1}^{n} \left( \frac{y_t - F_t}{y_t} \right) \times 100
\]

(14)

where \( y_t \) is the actual observation value at time \( t \), and \( F_t \) is the prediction value time \( t \). Also \( n \) is the number of the prediction values. Since the prediction has been done for a specific number of values with different time steps, the MPE is calculated as follows:

\[
MPE = \max \left\{ \left( \frac{y_t - F_t}{y_t} \right) \times 100, t = 1, \ldots, n \right\}
\]

(15)

3.6 Validation of the Proposed Swarm Intelligence Based Optimized Linear Prediction and Markov-Chain Based Linear Prediction Method For Light and Heavy Duty Electric Vehicles

Results of all Different Predictive Algorithms for 60 Data

To validate the results of proposed algorithms including optimized linear prediction and Markov-chain based linear prediction comparing to conventional linear prediction, all methods have been run for the same demanded power. As it is depicted in Figure 3.13, for 1 step ahead prediction with time step of 1 second, both proposed algorithms result in better performance than conventional linear prediction.
The same procedure was repeated for validating the results of the proposed algorithms including optimized linear prediction and Markov-chain based linear prediction comparing to conventional linear prediction. In this case, all three methods have been run
for the same demanded power and the results have been depicted in Figure 3.14. It has been shown that for 1 step ahead prediction with time step of 1.5 second, same as last results, both proposed algorithms result in better performance than conventional linear prediction.

To analyze the performance of all three prediction algorithms better, the error values of all algorithms for the above data and prediction values have been calculated and depicted in Figures 3.15 and 3-16. Figure 3.15 depicts the error of all three algorithm results compare to the real values. It has been derived from the prediction results for 1 second ahead prediction.

Figure 3.16 depicts the error of all three prediction algorithm results comparing to the actual values of the demanded power. The error of prediction methods are related to the results of forecasting 1.5 second ahead of demanded power. It is obvious that the error became worse than 1 second ahead prediction, but the proposed algorithm results are still better than conventional linear algorithm.

Figure 3.15. Error of all three prediction algorithms with respect to the real value of demanded power for 1 second ahead of forecasting.
Figure 3.16: Error of all three prediction algorithms with respect to the real value of demanded power for 1.5 second ahead forecasting.

<table>
<thead>
<tr>
<th>Time step</th>
<th>Prediction Method</th>
<th>Linear Prediction</th>
<th>Markov based linear</th>
<th>Optimized linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Second</td>
<td>ME(^1)</td>
<td>39.5563</td>
<td>32.144</td>
<td>24.2523</td>
</tr>
<tr>
<td></td>
<td>MAPE(^2)</td>
<td>5.1809</td>
<td>4.8151</td>
<td>4.1002</td>
</tr>
<tr>
<td></td>
<td>CFP(^3)</td>
<td>95.29</td>
<td>94.95</td>
<td>96.20</td>
</tr>
<tr>
<td>1.5 Second</td>
<td>ME</td>
<td>124.6206</td>
<td>45.8895</td>
<td>43.2175</td>
</tr>
<tr>
<td></td>
<td>MAPE</td>
<td>12.8197</td>
<td>9.3567</td>
<td>9.1443</td>
</tr>
<tr>
<td></td>
<td>CFP</td>
<td>72.95</td>
<td>82.93</td>
<td>86.32</td>
</tr>
<tr>
<td>3 Second</td>
<td>ME</td>
<td>142.5622</td>
<td>59.9595</td>
<td>44.2456</td>
</tr>
<tr>
<td></td>
<td>MAPE</td>
<td>37.5646</td>
<td>14.7110</td>
<td>10.1489</td>
</tr>
<tr>
<td></td>
<td>CFP</td>
<td>77.39</td>
<td>82.68</td>
<td>87.29</td>
</tr>
</tbody>
</table>

ME\(^1\): Maximum Error  
MAPE\(^2\): Mean Absolute Percentage Error  
CFP\(^3\): Correlation Factor Percentage
3.7 Conclusion

In this study, three prediction algorithms have been proposed to predict the power demand for the next step only. Precise prediction It is obvious that it precise predictions result in faster dynamics of the system and results in better and more efficient response of energy management system in electric vehicles. The linear prediction method proposed in this paper was found to be a very powerful tool of prediction, good for short term prediction of power demand in both light duty and heavy duty electric vehicles. The linear prediction method applied to light duty electric vehicle power demand data predicted the power profile which was good enough to be applied to an energy management system, but the prediction was further improved by filtering the measured power of light electric vehicle. However, the prediction for the heavy duty electric vehicle was found to be satisfactory even without filtering the measured power demand profile. A 97% correlation between the measured and predicted signal was obtained for the heavy duty electric vehicle and 89% correlation was obtained for the light duty electric vehicle. Due to finding the best values of model order and model length in linear prediction which can effectively improve the prediction results, swarm intelligence optimization proposed. It results in optimized linear prediction which comparing to linear prediction has lower error and better performance.

Another method which was proposed based on linear prediction is the combination of the Markov-chain and linear prediction using a nonlinear filter. It helps the linear prediction by using the Markov transition matrix is more efficient and improved. To keep the fast dynamics of the system as well as having better prediction results second order Markov chain combination with linear prediction have been applied.

According to these three prediction methods which expressed in this section, including linear prediction, optimized linear prediction using the Improve PSO, and Markov-chain based linear prediction, all methods result in more efficient and faster dynamics system. Finally it can be concluded that according to the all three different methods, Optimized linear prediction has the best performance. Another issue which should be considered is that applying higher order Markov chain (more than 2) probability matrix may result in better performance but will cause more calculation time.
Chapter 4
Motor Drive Optimal Design

4.1 Introduction

Inasmuch as the global demand for electric vehicle (EV) is growing rapidly in the recent years, nowadays EV designers’ challenge is to develop more optimal EV systems [1]-[4]. The motor drive system as one of the most important components in an electric vehicle structure has strong influence on the whole system performance. Therefore, many configurations and topologies for power converters are proposed by researchers to address inclusion of the most proper converter configuration into the EV drivetrain [5]-[8]. Multilevel converters are considered as an inevitable choice with respect to their merits including low distortion voltage and current characteristics, low output voltage deviation, low switching frequency, and small common mode voltage that results in lower stress on motor bearings [9]-[12].

The first multilevel converter was designed as a three-level, three-phase device in 1975 [13]. However, multilevel converters were employed in EV structure only in the last decade [14]. In spite of the fact that multilevel converters are widely used in EV/HEV structures, their major drawback is that the system consists of several power semiconductor switches resulting in less efficient converters due to switching power loss.

Authors in [15] due to decreasing the power loss, they reduced the voltage. Authors in [16]-[19] studied different voltage levels of 7 to 15 of output voltage. The authors in [20] conducted a comprehensive study to investigate the effect of DC input voltage variations due to the battery state-of-charge reduction for three converter topologies in EV applications. As an alternative approach to achieve efficient converter topologies, the effect of control strategies such as space vector modulation and pulse width modulation (PWM) were investigated in [21]-[23]. The authors in [24]-[27] proposed a modified diode clamped converter design to improve the DC/AC converter performance.

Therefore there are several topologies of DC/AC converters with their specific characteristics such as diode-clamped, flying capacitor, H-bridge, matrix converters, and cascaded inverters. Flying capacitor converter with easier extension of the voltage level
to higher levels has also some disadvantages. These converters include large capacitor banks, and an additional pre-charging circuitry. Also voltage imbalance among flying capacitors is an important issue in this converter.

Cascade inverters are proper converters for medium voltage, high power applications. But based on their configurations, they are more complicated than other types of converters and also more expensive. Therefore in diode-clamped converter, there is simplicity in extending the voltage to higher levels. and is widely used in medium and low power applications; in this study the proposed stacked matrix converter (SMC) converter has been compared with neutral point clamped (NPC) or diode-clamped converter. Also currently, H-bridge converter is the simplest and cheapest converter for driving AC motors in different power ranges. Therefore, manufacturers in auto industry prefer to use H-bridge converter, unless a new converter with advantages that can cope H-bridge simple structure, comes out.

Also, in spite of all the investigations carried out on different DC/AC converter topologies in electric vehicle applications, the lack of sufficient studies on the matrix converter (MC) topology is apparent while this technology has several merits and can be a proper topology for EV application. Moreover, from an EV manufacturers’ perspective, a comprehensive study on efficiency and performance of different motor drive configurations is required. Therefore, this section introduces a new design developed based on indirect matrix converter and compared it to both diode-clamped and H-bridge converter that are being increasingly used in industry.

Figure 4.1 shows a general schematic diagram of an indirect matrix converter. This topology benefits from better output voltage stability and less total harmonic distortion (THD) compared to other existing converter topologies. MC is inherently bi-directional that can regenerate energy. This converter has also the advantage of variable output voltage and frequency generation. In this section a new stacked matrix converter (SMC) is designed and developed. The proposed configuration not only possesses all the good features of MCs but also a reduced number of switches has led to a simpler design, more cost effective system, and more efficient structure with lower power dissipation.
To assess the performance of the proposed multilevel converter topology for EV applications, three-phase three-level diode clamped and an H-bridge converters and the drive circuitry are also designed and developed. Comprehensive studies are conducted to investigate the effect of each configuration on EV performance. This chapter is organized as follows. In Section 4.3, the three converter topologies are introduced. Section 4.4 presents the numerical investigation results on time, harmonic, and efficiency analyses. Section 4.5 includes the experimental results obtained by conducting several tests on the proposed SMC and diode clamped converters.
4.2 Motor Drive Topologies in Electric Vehicle Applications

Multilevel converters are widely used in several applications such as electric arc furnaces, and heavy- and light-duty electric vehicle motor drives due to their high efficiency and low total harmonic distortion. In this section, three topologies of such converters are investigated to select the most suitable configuration that can be utilized in EV application.

4.2.1 Three-phase, Three-level H-bridge Converter

Figure 4.2 shows the circuit diagram of a three-phase three-level H-bridge converter. As illustrated in this figure, a three-phase H-bridge converter embracem four switches in each phase controlled by a SPWM signal to generate three-level voltage at the output. The switching scheme of this converter is presented in Table 4-1 in Appendix B. The output phase voltages can be determined using (4.1) which is based on the switching combination profile and the DC-link voltage, $2V_C$. ($S_{a1}=1$ when the corresponding switch is on and $S_{a1}$ is zero when the corresponding switch is off) [68].

$$V_{as} = 2V_{DC} \left( \frac{2}{3} S_{a1} - \frac{1}{3} S_{b1} - \frac{1}{3} S_{c1} \right)$$

$$V_{bs} = 2V_{DC} \left( \frac{2}{3} S_{b1} - \frac{1}{3} S_{a1} - \frac{1}{3} S_{c1} \right)$$

$$V_{cs} = 2V_{DC} \left( \frac{2}{3} S_{c1} - \frac{1}{3} S_{b1} - \frac{1}{3} S_{a1} \right)$$

4.2.2 Three-phase Three-level Diode-Clamped Converter

In diode clamped converters a capacitor bank is used to form different voltage levels at the DC link. Figure 4.3 illustrates a three-phase three-level diode-clamped converter where the neutral wire is created by two capacitors. In this topology, the clamped diode along with the middle switches provides a route that facilitates accessing the neutral wire.

The switching scheme for this converter topology is demonstrated in Table 4-2 in Appendix B. The control signal applied to the switches is designed to meet the

68
requirements for all the operating modes. When the converter is connected to a load, the capacitor voltage might be unbalanced. Therefore, to prevent unbalanced operational mode, parallel resistances will be installed at the capacitor bank conjunction. Although increasing the voltage level results in more accurate results, it leads to a more complex circuitry and a more complicated switching process.

In addition, considering the maximum voltage the diodes can tolerate, the diode-clamped converters with a higher level than level five are not practical. Considering the middle of the DC-link as the point of reference ‘$n$’, a three-level output voltage is generated at each phase terminal. Accordingly, the phase voltage can be determined using (4.2).

$$V_{xn} = V_{DC} \left( S_{x(1,2)} - S_{x(3,4)} \right) \tag{4.2}$$

Figure 4.3. Schematic diagram of a three-phase, three-level diode-clamped converter system with grounded $n$. 
$$V_{as} = \frac{2}{3} V_{DC}\left(m_{a1} - m_{a3} - \frac{1}{2}(m_{b1} - m_{b3} + m_{c1} - m_{c3})\right)$$
$$V_{bs} = \frac{2}{3} V_{DC}\left(m_{b1} - m_{b3} - \frac{1}{2}(m_{a1} - m_{a3} + m_{c1} - m_{c3})\right)$$
$$V_{cs} = \frac{2}{3} V_{DC}\left(m_{c1} - m_{c3} - \frac{1}{2}(m_{a1} - m_{a3} + m_{b1} - m_{b3})\right)$$

$$V_{ab} = V_{a0} - V_{b0} = V_{DC}\left(m_{a1} - m_{a3} - m_{b1} + m_{b3}\right)$$
$$V_{bc} = V_{b0} - V_{c0} = V_{DC}\left(m_{b1} - m_{b3} - m_{c1} + m_{c3}\right)$$
$$V_{ca} = V_{c0} - V_{a0} = V_{DC}\left(m_{c1} - m_{c3} - m_{a1} + m_{a3}\right)$$

(4.3)

where $V_{xn}$ is the output voltage of the phase “x” ($x \in \{a, b, c\}$) and $S_{x(1,2)}$ and $S_{x(3,4)}$ represent the switch status of the upper and the lower pair of the switches at the phase $x$, respectively. $S_{x(m,n)}$ returns value of one when both switches “m” and “n” are on and zero otherwise. The output voltages are determined using (4.3)

### 4.2.3 Three-phase Three-Level Stacked Matrix Converter

In motor drive applications, the matrix converter topology has been recently used by researchers. In this chapter a new three-level stacked matrix converter (SMC) is presented. The schematic diagram of the converter is depicted in Figure 4.4. As seen in this figure, the proposed configuration consists of four pairs of MOSFET-diode and two bi-directional switches at each phase. Using the bi-directional switches at each phase leg provides this new converter design with the advantage of having zero voltage level with less number of the switches. The SMC converter has the advantage of variable output voltage and frequency generation. However, presence of the excess bi-directional switches makes the structure more complex and that results in a more complicated control system in comparison to the conventional converters. The switching profile for SMC converters is presented in Table 4-2 in Appendix C.

### 4.3 Control and Modulation Strategy

Switching modulations that are used in multilevel inverters according to the switching frequency, are classified to fundamental switching frequency and high switching frequency PWM. In this study high switching frequency PWM is the method of
modulation. This method includes space vector PWM and sinusoidal PWM or SPWM SPWM which is used in this chapter is the phase-shifting technique in order to reduce the voltage harmonics. In SPWM method the carrier frequency which is compared with fundamental sinusoidal should be an odd multiplication of the fundamental frequency. The carrier frequency should be chosen properly that results in minimum total switching loss and conduction loss. In this study the open-loop SPWM method for all three converters has been used and figure 5 shows the SPWM structure with phase-shifting technique of fundamental for all phases. Figures 4.6 to 4-8 depict the SPWM signals coming to gates based on switching Table 4-2, 3, and 4 for one phase of all three converters [68].
Figure 4.6. Gate signals of one phase of diode-clamped converter based on SPWM technique.

Figure 4.7. SPWM technique gate signals of a phase of H-bridge converter.
4.4 Numerical Analysis of Different Converter Topologies

The aforementioned converter topologies are implemented in MATLAB modeling. These models are also integrated with the control system model to represent the whole system.

4.4.1 Harmonic Analysis of Three-phase Output Voltage for the Converter Topologies under Investigations

Time and frequency analyses are carried out on different converter topologies up to the input voltage of $V_{in} = 400$ V. Figures 4.9 to 4-11 depict the three-phase output voltage of each converter and their corresponding harmonic analysis results. As can be seen in the signal spectrum, there are several harmonic orders with the 40% of the fundamental frequency magnitude. However, their frequencies are 20 times larger than the fundamental frequency. Therefore, they can be easily eliminated from the signal by utilizing a low-pass filter at the output of the converter. Total harmonic distortion of the signal can be mathematically calculated using (4.4) [68].
where $H_n$ is the $n$th harmonic amplitude in the signal spectrum. The THD calculation results for all the converter topologies investigated in this section confirm that the SMC converter configuration produces the best performance.

To reduce the magnitude of the non-fundamental harmonics of the output waveform, the converter is loaded with a Y-connected 3-phase load. The analysis of the phase-to-neutral voltage is demonstrated in Figures 4.12 to 4-14 for all the converter types. In these figures, nine voltage levels can be differentiated that make the signal more similar to a sinusoidal waveform. This is verified by the results of harmonic analysis demonstrated in Figures 4.12 to 4-14. The results of the investigation verify that the non-fundamental frequency harmonic magnitudes are considerably reduced in comparison to the corresponding harmonic magnitudes calculated in the previous analysis. Furthermore, the THD analysis on the signal spectrum indicates approximately 50% improvement.

Also, as illustrated in Figures 4.9 and 4-12, the harmonic analysis for the proposed SMC converter results in lower non-fundamental frequency harmonic magnitude for both phase and line-to-line voltages in compare to the other two topologies under the investigations.

Figure 4.9. SMC converter phase-to-neutral voltage and the total harmonic distortion.
Figure 4.10. Diode-clamped phase-to-neutral voltage and the total harmonic distortion.

Figure 4.11. H-bridge phase-to-neutral voltage and the total harmonic distortion.

4.4.2 Efficiency and Performance Analysis of Three Converter Models under the Investigations

As the motor drive components play a vital role in EV power distribution profile, the performance of the powertrain is directly affected by the efficiency of the DC/AC converters. In this study, a comprehensive assessment of the efficiency of the three converter types is carried out. The investigations assist the designers in selecting the most suitable converter configuration for EV application [68].
The conduction power dissipation is used to determine the total power loss of the converters. The power consumed by the switches is given by (4.5).

\[
P_{SW}(t) = i_{SW}(t) \cdot v_{SW}(t)
\]  

(4.5)

where \(i_{SW}\) and \(v_{SW}\) are the instantaneous current and voltage, respectively. The forward voltage of a switch is described by (4.6), where \(V_{SW\text{-sat}}\) is the forward voltage drop across the device when the drain current is small.

\[
v_{SW}(t) = v_{SW\text{-sat}} + R_{SW} \cdot i_{SW}(t)
\]  

(4.6)
Consequently, the instantaneous power can be derived using (4.7)

\[ P_{SW}(t) = i_{SW}(t) \ast (v_{SW-sat} + R_{SW} \ast i_{SW}(t)) \] (4.7)

Therefore, the average MOSFET power loss during conduction over a signal period, \( T \), can be obtained as

\[ P_{SW} = \frac{1}{T} \int_{0}^{T} P_{SW}(t) dt. \] (4.8)

Correspondingly, the conduction loss of a diode can be estimated by:

\[ P_{D}(t) = i_{F}(t) \ast (v_{F0} + R_{F} \ast i_{F}(t)) \] (4.9)

where \( V_{F0} \) is the forward voltage drop across the diode when the forward current of the device \( i_{F} \) approaches zero and \( R_{F} \) is the approximate on-state resistance of the diode. The diode average power dissipation, \( P_{D} \), can be calculated using (4.10).

\[ P_{D} = \frac{1}{T} \int_{0}^{T} P_{D}(t) dt \] (4.10)

According to the diode-clamped structure shown in Figure 3, the total conduction power loss dissipated in this type of the converter is given by:

\[ P_{T} = P_{D1} + P_{D2} + P_{SW1} + P_{SW2} + P_{SW3} + P_{SW4} \] (4.11)

Employing 4.12, the efficiency of the converter can be calculated considering \( P_{T} \) as the
input power of the system.

\[ \eta = \frac{P_I - P_T}{P_I} \] (4.12)

The conduction power loss equations for the SMC and H-bridge converters can be calculated using (4.13) and (4.14), respectively.

\[ P_T = P_{D1} + P_{D2} + P_{SW1} + P_{SW2} + P_{SW3} + P_{SW4} + P_{SW5} + P_{SW6}. \] (4.13)

\[ P_T = P_{SW1} + P_{SW2} + P_{SW3} + P_{SW4} + P_{SW5} + P_{SW6}. \] (4.14)

In order to verify the calculated efficiency of the proposed SMC converter with the ones for the diode-clamped and H-bridge converters, the experimental set-up in Figure 4.15 which consists of a power analyzer and an equipped scope with data acquisition system, has been used.

Figure 4.16. a depicts the energy loss of the switch \( SW_{a1} \) in the SMC converter. Since all the switches \( SW_{a1-4} \) are working similarly at same switching frequency and time period measurement of one switch’s loss, i.e., \( SW_{a1} \), would be enough.

Figure 4.15. Experimental set-up for calculating the efficiency of the converters.
Figure 4.16. a) Energy loss of switches $SW_{a1}$ in SMC converter for 0.08 second. b) Energy loss of switches $SW_{a5,6}$ in SMC converter for 0.08 second.

Figure 4.16b presents the corresponding energy loss of the two switches $SW_{a5,6}$ which work simultaneously and similar to each other in SMC converter. Therefore the total conduction power loss of this converter which calculates in simulation would be:

$$P_{SWa1,2,3, and 4} = \frac{E_{SWa1,2,3, and 4}}{t_{simulation}}$$  \hspace{1cm} (4.15)
Similarly for diode-clamped and H-bridge converters, the conduction power loss has been measured and presented in Figures 4.17a, b, and c. Since switches $SW_{a1,4}$ works at same frequency and time period, therefore, the energy loss of switches $SW_{a1,4}$ is the similar and depicted in Figure 4.17a. Figure 4.17b shows the energy loss of switches $SW_{a2,3}$, which are working in similar fashion and consequently have same energy loss. Figure 4.17c also depicts the energy loss of two clamped diodes which have same losses in diode-clamped converter.

Therefore the total conduction power loss of diode-clamped converter will be:

\[ P_T = P_{SW_{1,4}} + P_{SW_{2,3}} + D_{1,2} \]  \hspace{1cm} (4.18)

Finally, same as previous measurements, H-bridge converter’s conduction loss is depicted in Figure 4.18. Since all switches are working with similar switching frequency and time period, they all have same energy and power loss as illustrated in Figure 4.18.

Therefore the total power loss is:
Since a similar input power is used for all three configurations, the efficiencies of the three converters are calculated as follow:

\[
\eta = 1 - \frac{P_{\text{loss}}}{P_{\text{input}}} \tag{4.20}
\]
Based on the (4.20) the efficiencies of SMC, diode-clamped and H-bridge converters are 90%, 89%, and 90.5% respectively.

The efficiency and performance analysis of the aforementioned converter configurations are presented in table 4-1. As presented in this Table, the H-bridge and SMC structures are more efficient configurations in comparison to the diode-clamped configuration. This is due to the fact that there is a smaller number of switches in the structure. Moreover, as shown in this Table, the SMC configuration shows a smaller THD compared to other two DC/AC converter topologies.

By contrast, the investigations indicate that both SMC and H-bridge converters possess better efficiency than diode-clamped converter topology. In addition to the novel design

<table>
<thead>
<tr>
<th>Converter</th>
<th>THD (no-load)</th>
<th>THD (Y-connected load)</th>
<th>Efficiency</th>
<th>Cost</th>
<th>Number of switches</th>
<th>Number of clamped diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stacked matrix</td>
<td>51.38</td>
<td>28.15</td>
<td>90%</td>
<td>-</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Diode-clamped</td>
<td>52.52</td>
<td>34.59</td>
<td>89%</td>
<td>-</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>H-bridge</td>
<td>67.5</td>
<td>39.5</td>
<td>90.5%</td>
<td>cheapest</td>
<td>12</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.18. Energy loss of Switches $SW_{a1,2,3,4}$ in H-bridge converter for 0.08 second.

TABLE 4-1. COMPARISON OF THE DC/AC CONVERTER TOPOLOGIES
of the SMC converter, which results in better THD performance, the control scheme used for SMC configuration is simpler. Furthermore, less value of power dissipation and simpler controller result in a more economical solution [68].

4.5 Reliability and Fault Analysis of H-bridge, Diode-Clamped, and the Proposed SMC

Regarding the reliability analysis of the three converters, both short-circuit and open-circuit faults of phase-to-line and line-to-line faults have been analyzed. Results are presented as follows:

Figures 4.19a, b, and c shows the effect of open-circuit fault of one phase of all three converters. As it can be seen, the SMC converter shows better harmonic performance as compared to the diode-clamped and H-bridge converters. This will result in lower core and iron loss in motors and as a result higher efficiency. It also will decrease the opposite torque of the harmonics against the motor torque.

Figures 4.20a, b, and c show the open-circuit fault of line-to-line voltage of SMC, diode-clamped and H-bridge converters. Following results confirm that the proposed SMC converter configuration has better THD performance.

Figures 4.21a, b, and c and Figures 4.22a, b, and c show the short-circuit faults of phase to phase and phase to line voltage of all three SMC, Diode-clamped and H-bridge converters, respectively. As it can be seen, the proposed SMC converter configuration results in much better THD performance comparing to diode-clamped and H-bridge converters.
Figure 4.19a. Phase-to-phase open-circuit fault of H-bridge converter.

Figure 4.19b. Phase-to-phase open-circuit fault of diode-clamped converter.
Figure 4.19c. Phase-to-phase open-circuit fault of SMC converter.

Figure 4.20a. H-bridge converter phase-to-line open-circuit fault.
Figure 4.20b. Diode-clamped converter phase-to-line open-circuit fault.

Figure 4.20c. SMC converter phase-to-line open-circuit fault.
Figure 4.21a. Phase to phase-short-circuit fault of H-bridge converter.

Figure 4.21b. Phase-to-phase short-circuit fault of diode-clamped converter.
Figure 4.21c. Phase-to-phase short-circuit fault of SMC converter.

Figure 4.22a. H-bridge converter phase-to-line short-circuit fault.
Figure 4.22b. Diode-clamped converter phase-to-line short-circuit fault.

Figure 4.22c. SMC converter Phase-to-line short-circuit fault.
4.6 **Design and Experimental Investigations Setup on the Diode-clamped and SMC Converter Topologies**

The numerical investigations presented in Section 4.4 indicate that based on the harmonic performance and efficiency requirements for EV applications, the SMC configuration can be considered as the best solution for the motor drive in EV applications. This section presents experimental investigations based on the diode-clamped converter and the proposed SMC inverter to verify the results obtained in this research. The three-phase three-level SMC and diode-clamped converter and their driver circuits along with the control unit are illustrated in Figure 4.23. As shown in this figure the gate control signals are generated using a real-time simulator (Opal-RT). These signals are applied to the switches through IR2110 MOSFET drivers. The driving board is designed to provide 15 V and 1 A control gate signals. The bootstrap capacitor is designed to satisfy following inequality [8].

\[
C_{BOOT} \geq \frac{Q_{TOT}}{\Delta V_{GS}}
\]  

(4.21)

where \( Q_{TOT} \) is the bootstrap charge needed to turn on the switches and \( \Delta V_{GS} \) is the maximum voltage drop across the gate and source of the MOSFETs [69]. Consequently, the bootstrap capacitor used in the deriver circuit is calculated to be 3.3 \( \mu F \). In addition to
the capacitor, the bootstrap circuit includes an ultra-fast diode and a 15 Ω bootstrap resistor.

Figures 4.24 and 4.25 show the phase voltage of the diode-clamped and the proposed SMC converter under the high current load test, respectively. According to these figures, SMC converter generates distortion-free three-level phase voltage. But diode-clamped converter generates distorted three-level phase voltage, which is the result of high load current and its effect on voltage stability. Figures 4.26 and 4.27 confirm that the same rule can be applied to the line-to-line voltage of the converters.

Both diode-clamped and the proposed SMC converters possess satisfactory results on no-load working condition according to the simulation results in the previous section. However, in full load working situation as discussed in this section, the proposed SMC converter can provide better results. This also validates the THD analysis carried out in this study. Tables 4-2 and 4-3 in Appendix demonstrate the switching scheme that creates different voltage levels in full-load.

Stability of the output signal at the maximum loading condition is a major problem in converter design applications. To verify the converter performance to maintain the state of equilibrium, a large current is drawn from the convertor output. This can be concluded from the signal graph illustrated in Figures 4.12 to 4.15. Based on the investigations conducted on both converter models, the proposed stacked matrix converter significantly delivers better results in terms of voltage stability and total harmonic distortion.

There are some spikes in the figures which come back to the resolution of the oscilloscope which has been used here. But the purple lines which clearly depict the desired wave form of the converters line to line voltage for both inverters has been shown in following figures.
Figure 4.24. Experimental results of three-level phase-to-line voltage of the diode-clamped inverter topology.

Figure 4.25. Experimental results of three-level phase-to-line voltage of the SMC inverter topology.

Figure 4.26. Experimental results of three-level line-to-line voltage of the diode-clamped inverter topology.
4.7 Conclusion

In this study, a new configuration for stack matrix three-phase DC/AC converters is proposed. Comprehensive performance analysis is carried out on the proposed converter model and two conventional DC/AC converter configurations namely diode-clamped and H-bridge converters. The line-to-line and phase voltage output waveforms of all the three topologies under investigations have been studied. Analysis on the converter output voltage harmonics as well as the converter efficiency reveal that the proposed SMC configuration possesses less THD and better efficiency in comparison with the two other topologies. Therefore, in the EV applications, SMC DC/AC converter can be considered as the best choice. Nevertheless, the H-bridge and diode clamped converters can operate with simpler control strategy when they are designed for the fifth-level output voltage and higher.
Chapter 5

Conclusions, contributions, and Suggested Future Work

5.1 Conclusions

Electrified vehicles are being used increasingly worldwide and designs are being changed continuously to improve their mechanical and electrical performance.

As explained in this study, the most important part of EVs that significantly contribute to EV performance is the power train. It involves energy sources, DC/DC converter, and DC/AC motor drive.

This study aimed at designing an optimal configuration of power train in the battery/UC hybrid sources of light/heavy duty electrified vehicle. Therefore the power train system has been divided into three parts.

Firstly, optimal sizing of hybrid sources of battery/UC has been designed. In this part, a comprehensive objective function including all factors of cost, space, weight, and acceleration time has been expressed. Technical and customer preferences and manufacture related factors have been included as constraints.

Improved swarm intelligence, which is more reliable and faster than other optimization algorithms, has been used for the optimal sizing. It has been shown that this algorithm is fast enough to be used as online EMS too and can converge to optimal results in a short time.

To improve the EV system in DC/DC converter part, the idea of modifying the system by speeding up the system dynamics has been used. To achieve this, since the EV system itself is not fast enough, a prediction based controller can help the DC/DC converter dynamics. Consequently, two new forecasting algorithms have been developed and compared to the well-known linear prediction one.
In short term prediction area, linear prediction is considered to be one of the most efficient algorithms. Therefore, two new algorithms namely optimized linear prediction and Markov-chain based linear prediction have been developed and their performance has been compared to the linear prediction algorithm.

Finally to improve the DC/AC motor drive converter, a novel stacked matrix converter (SMC) has been developed and tested experimentally. The new design was compared to two most common DC/AC converters including diode-clamped and H-bridge converters. Efficiency, harmonic distortion, and voltage stability have been studied for all three models.

In this study, the findings are supported through simulations and experimental results.

The contribution of this work can be summarized as follow:

- Based on the background studies in this area and expressing the unsolved issues, the design of electric vehicle can be modified significantly if its powertrain improved by three important parts:
  1. Energy storage; battery and ultra-capacitor based hybrid ESS has been chosen in this study
  2. DC/DC converters considering any design
  3. DC/AC converters including any available design

To achieve all the goals, the following contributions have been achieved:

Novel powertrain design of EV with higher efficiency, faster dynamics and optimal configuration based on following contributions:

1. Optimal configuration of hybrid sources using of new energy management scenarios and improved particle swarm optimization.

2. Design of optimal configuration of hybrid sources in a way that is fast enough if it is used as an online energy management system in EV.
3. Novel prediction based control strategies with high accuracy and low error of prediction to increase the efficiency of the system by improving the dynamics of the system.

4. Design a novel DC/AC converter with better performance including lower total harmonic distortion, voltage stability and lower loss.

5. Comprehensive analysis of novel design with other common converters in all technical and economic aspects.

5.2 Suggested Future Work

A number of ideas are presented in this section highlighting suggested extensions of the work in this research area. Key elements are described as follows:

To design an optimal size for hybrid power sources, many performance constraints as explained in this study have been considered. However, by using a dynamic model of the power sources for the sizing algorithm, better and more realistic results could be obtained.

The sizing algorithm can be used as an online energy management system since it is fast enough. It is highly recommended to use the dynamic model of EMS and apply the proposed algorithm online plus experimental results.

Since the hybrid of Markov-chain based linear prediction results in a better prediction, it is suggested to increase the Markov model and if possible, a faster algorithm to form the third order or more of transition matrix of Markov chain in order to improve the forecasting performance. Also, robustness in the predictive controller plays an important role in the performance of the system.

To find out the best topology of the motor drive DC/AC converter, simulation and experimental tests for more DC/AC topologies will provide better comparative results as well as applicability studies can also be performed for the topology developed.
In this study three phase three level inverters have been investigated, it is worthy to analyze the improvement of the harmonics assessment and on the other hand the increase in total loss and cost of these converters if the number of levels and as its result the number of levels increases.

It is very important to consider the inter-harmonics and sub-harmonics i.e. TIHD and TSHD to see if the new developed design is still better than other available designs [73].

It is a good idea to apply the closed loop controller to all the three design of this research and find out the best tradeoff between switching loss and conduction loss to get the best efficiency.
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APPENDICES

Appendix A

In this appendix, information is given on ‘correlation coefficient’ assessment. In probability theory and statistics, correlation, also called correlation coefficient, indicates the strength of relationship between two random variables or signals. Considering two signals, $X(t)$, and $Y(t)$, the correlation coefficient can be obtained from [11]:

$$
Corr(X, Y) = \int_{-\infty}^{\infty} X(t)Y(t)dt
$$

(A.1)

where, $T$, is called the lag and the correlation coefficient is a function of this lag. In this paper the lag, $T$, is set to be zero. This means correlation between $X(t)$ and $Y(t)$ without any lag. In this paper, $X(t)$, is the measured power and, $Y(t)$, is the predicted power by linear prediction. The value of correlation coefficient can be between -1 to +1 (or -100% to +100%). A value equal to 100% means the two signals are exactly identical and a value equal to zero means the two signals has no correlation and are independent. A value less than 0.3 means small correlation, a value between 0.3 and 0.5 means medium correlation, and, a value more than 0.5 means large correlation. A negative value (for eg. -100%) means the signals are identical but where one signal increases by a small amount, the other signal decreases exactly by the same amount.
Appendix B

TABLE 4-1
THREE-LEVEL H-BRIDGE CONVERTER FUNCTIONING PRINCIPLE

<table>
<thead>
<tr>
<th>Switching Combinations</th>
<th>Output</th>
</tr>
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<tbody>
<tr>
<td>$SW_{a1}$</td>
<td>$SW_{a2}$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
### Appendix C

#### Table 4-2

<table>
<thead>
<tr>
<th>Switching combinations</th>
<th>Output phase voltage</th>
<th>Output line-to-line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{an}$</td>
<td>$V_{bn}$</td>
</tr>
<tr>
<td>Sw_{a1}, Sw_{a2}</td>
<td>$V_{DC}$</td>
<td>$V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a2}, Sw_{a3}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sw_{a3}, Sw_{a4}</td>
<td>$-V_{DC}$</td>
<td>$-V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a1}, Sw_{b2}</td>
<td>$2/3V_{DC}$</td>
<td>$-1/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{b2}, Sw_{a2}</td>
<td>$-1/3V_{DC}$</td>
<td>$2/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{b2}, Sw_{a4}</td>
<td>$1/3V_{DC}$</td>
<td>$1/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a2}, Sw_{b1}</td>
<td>$-2/3V_{DC}$</td>
<td>$1/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{b1}, Sw_{b2}</td>
<td>$1/3V_{DC}$</td>
<td>$-2/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{b3}, Sw_{b4}</td>
<td>$-2/3V_{DC}$</td>
<td>$1/3V_{DC}$</td>
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<tr>
<td>Sw_{a3}, Sw_{a4}</td>
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<td>$-2/3V_{DC}$</td>
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<tr>
<td>Sw_{b3}, Sw_{b4}</td>
<td>$2/3V_{DC}$</td>
<td>$2/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{b4}, Sw_{a2}</td>
<td>$-4/3V_{DC}$</td>
<td>$2/3V_{DC}$</td>
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<tr>
<td>Sw_{b4}, Sw_{a4}</td>
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<tr>
<td>Sw_{a2}, Sw_{b2}</td>
<td>$2/3V_{DC}$</td>
<td>$-4/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a4}, Sw_{b2}</td>
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<td>$4/3V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a1}, Sw_{b2}</td>
<td>$V_{DC}$</td>
<td>0</td>
</tr>
<tr>
<td>Sw_{a2}, Sw_{b4}</td>
<td>0</td>
<td>$V_{DC}$</td>
</tr>
<tr>
<td>Sw_{a4}, Sw_{b1}</td>
<td>$-V_{DC}$</td>
<td>0</td>
</tr>
<tr>
<td>Sw_{a1}, Sw_{b4}</td>
<td>$V_{DC}$</td>
<td>$-V_{DC}$</td>
</tr>
</tbody>
</table>
## Appendix D

### Table 4.3

The Three-Level SMC Converter Switching Profile

<table>
<thead>
<tr>
<th>Switching combinations</th>
<th>Output phase voltage</th>
<th>Output line-to-line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{an}$</td>
<td>$V_{bn}$</td>
</tr>
<tr>
<td>Swa1, Swb2 Swa2</td>
<td>V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swa6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd2 Swa2</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd2 Swa2</td>
<td>1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd2 Swa2</td>
<td>1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-1/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>-4/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa3, Swd6</td>
<td>-4/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
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<tr>
<td>Swa3, Swd6</td>
<td>2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-4/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
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<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>-2/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>4/3V&lt;sub&gt;DC&lt;/sub&gt;</td>
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<td>Swa3, Swd6</td>
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<td>V&lt;sub&gt;DC&lt;/sub&gt;</td>
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<td>V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Swa1, Swd4 Swd3, Swd4</td>
<td>V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>-V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
Appendix E

One of the main indexes of harmonics content or waveform harmonic distortion assessment is Total Harmonics Distortion (THD). THD is based on any integer multiples of fundamental frequency. Non-filtered harmonic signal content unwanted harmonics which should remove by filtering or reduced by any modified design. Equation below depicts the calculation of THD which is a standard equation of calculation THD. THD reduction after filtering is same as increasing amplitudes of fundamental and reducing the harmonic amplitudes.

\[
THD = \sqrt{\frac{\sum_{h=3}^{n} a_h^2}{a_1}}
\]

IEC 610004-7 standard, includes indexes regarding of inter-harmonics as harmonic phenomena development.. If there were inter-harmonics in a harmonic signal, the Total Inter-Harmonic Distortion, TIHD, can be found by equation below.

\[
TIHD = \sqrt{\frac{\sum_{i=1}^{n} a_i^2}{a_1}}
\]

Where “i” is the total number of inter-harmonics which considered and n is the total frequencies including sub harmonics.

If the sub-harmonics were noticeable, it should be calculated separately and this leads to a factor which called total sub-harmonic distortion, TSHD. TSHD is defined by equation below.

\[
TSHD = \sqrt{\frac{\sum_{s=1}^{S} a_s^2}{a_1}}
\]
Where, “$S$” is the total frequencies which exist in sub frequency of fundamental sequence. Other distortion factors and statistic assessment of harmonics can be used for sub-harmonic assessment in power systems.

$THD, TIHD$ and $TSHD$ factors for result waveform during the experiment is a proper tool for assessment.
Appendix F

In order to model the DC/DC boost converter, state space average technique is used. Figure F-1 represents a schematic of a DC-DC boost converter modeled in this study. There are two different states of the converter depending on whether switches are ON or OFF. $t_{on}$ is the time of sub-interval of the converter when the switch 1 is ON and switch 2 is OFF. Equation 1 represents the system dynamics in this interval.

$$-V_{in} + I_L (r_L + r_s) + L \frac{dI_L}{dt} = 0$$

$$RC \frac{dV_c}{dt} + V_c = 0$$

(F-1)

Corresponding system equations for the $t_{off}$ (switch 1 is OFF, switch 2 is ON) subinterval of the converter is expressed by the following:

$$-V_{in} + I_L (r_L + r_s) + V_c + L \frac{dI_L}{dt} = 0$$

$$RC \frac{dV_c}{dt} + I_{out} - I_L = 0$$

(F-2)

DC model of the system by using the average technique is:

$$-V_{in} + I_L (r_L + r_s) + V_c + L \frac{dI_L}{dt} + D' V' = 0$$

$$C \frac{dV_c}{dt} + \frac{D}{R} V_c + D' I_{out} - D' I_L = 0$$

(F-3)

Inserting the AC perturbation to the DC model, the state space AC average equation derived from the two ON and OFF states in converter equilibrium point is as given in (F-4). Neglecting the higher order terms and using the values shown in Figure F-1, the system parameter is defined as in (F-5). Therefore the controls to high-side voltage, low-side voltage and output current transfer function are obtained in (F-6).
The DC/DC converter parameters have been considered as follow: \( r_L = 0.2\Omega \); \( L = 220\text{mH} \); \( V_{\text{in}} = 12\text{v} \); \( r_s = 0.2\Omega \); \( r_c = 0.1\Omega \). According to these values, following state space average matrices has been calculated:

\[
\begin{align*}
    \dot{i}_L &= -\frac{(r_L + r_s)}{L}(i_L + i_L) - \frac{(D + d)}{L}(V_c + v_c) + \frac{V_{\text{in}}}{L} \\
    \dot{v}_c &= \frac{(D + d)}{C}(i_L + i_L) + \frac{(D + d)}{RC}(v_c + v_c) - \frac{(D + d)}{C}(i_{\text{out}} + i_{\text{out}}) \\
A &= \begin{bmatrix} -1500 & -2500 \\ 2272 & -51 \end{bmatrix},
B = \begin{bmatrix} -1500 & -120000 \\ 0 & 85950 \end{bmatrix},
C = \begin{bmatrix} 0 & 1 \end{bmatrix}
\end{align*}
\]

(F-4)

To verify the obtained model, the system has been designed in PSIM using the AC sweep in switch mode. The results have been compared with the state space average model and are represented in Figure F-2. It is illustrated that the state space average model adeptly represents the behaviour of the DC-DC boost converter. Subsequently it can be used in any model based observer and controller of Dc/DC converter.

To verify the obtained model, the system has been designed in PSIM using the AC sweep in switch mode. The results have been compared with the state space average model and are represented in Figure F-2. It is illustrated that the state space average model adeptly represents the behaviour of the DC-DC boost converter. Subsequently it can be used in any model based observer and controller of Dc/DC converter.
Fig. F-2: Derived average model frequency response compared to PSIM results

The modeling of the DC/DC converter using state space model technique has been verified with its frequency response with that of a switch mode model.
Appendix G

Calculating 2nd Order Markov Chain Matrix

For $i$ 1 to $n$
    \[
    \text{Count1}(P_{iP_{i+1}}) += 1
    \]
    \[
    \text{Count2}(P_{iP_{i+1}}) += 1
    \]
End

- To calculate each element of the matrix following approach should be used:
- NOS: Number of States of demanded power

For $k$ 1 to $\text{NOS}^2$
    For $j$ 1 to $\text{NOS}$
        \[
        p(k, j) = \frac{\text{Count2}\left(\text{Ceil}\left(\frac{k}{\text{NOS}}\right)k - \left[\text{Ceil}\left(\frac{k}{\text{NOS}}\right)-1\right] \times \text{NOS}, j\right)}{\text{Count1}\left(\text{Ceil}\left(\frac{k}{\text{NOS}}\right)k - \left[\text{Ceil}\left(\frac{k}{\text{NOS}}\right)-1\right] \times \text{NOS}\right)}
        \]
    End
End
Appendix H

International Rectifier

IR2110(S)/IR2113(S) & (PbF)

HIGH AND LOW SIDE DRIVER

Features
- Floating channel designed for bootstrap operation
- Fully operational to ±500V or ±600V
- Tolerant to negative transient voltages ±5V
- Gate drive supply range from 10 to 20V
- Undervoltage lockout for both channels
- 3.3V logic compatible
- Separate logic supply range from 3.3V to 20V
- Logic and power ground ±5V offset
- CMOS Schmitt-triggered inputs with pull-down
- Cycle by cycle edge-triggered shutdown logic
- Matched propagation delay for both channels
- Outputs in phase with inputs
- Also available LEAD-FREE

Product Summary

<table>
<thead>
<tr>
<th>Feature</th>
<th>IR2110</th>
<th>IR2113</th>
</tr>
</thead>
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<td>600V max.</td>
</tr>
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<td>I_O+/I_O-</td>
<td>2A / 2A</td>
<td></td>
</tr>
<tr>
<td>VOUT</td>
<td>10 - 20V</td>
<td></td>
</tr>
<tr>
<td>t_on/off (typ.)</td>
<td>120 &amp; 94 ns</td>
<td></td>
</tr>
<tr>
<td>Delay Matching</td>
<td>(IR2110) 10 ns max.</td>
<td>(IR2113) 20 ns max.</td>
</tr>
</tbody>
</table>

Description
The IR2110/IR2113 are high voltage, high speed power MOSFET and IGBT drivers with independent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. Logic inputs are compatible with standard CMOS or LSTTL output, down to 3.3V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 500 or 600 volts.

Typical Connection

(Refer to Lead Assignments for correct pin configuration. This diagram shows electrical connections only. Please refer to our Application Notes and Design Tips for proper circuit board layout.)
Appendix I

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Title: Short term power demand forecasting in light- and heavy-duty electric vehicles through linear prediction method

Conference Proceedings: Transportation Electrification Conference and Expo (TEC), 2012 IEEE

Author: Sangdehi, M.M.; Iyer, K.L.V.; Mukherjee, K.; Kar, N.C.

Publisher: IEEE

Date: 18-20 June 2012

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