AN AVERAGE MODELING APPROACH OF HYBRID POWER SYSTEMS
FOR USE IN MOBILE REFRIGERATION APPLICATIONS

BY
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THESIS
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ABSTRACT

This thesis presents averaging-based models of hybrid electric power systems for refrigeration units in delivery trucks. The background of the mobile refrigeration industry is stated, and the motivation of the proposed hybrid-powered ac motor drive is discussed. The model is intended to be used for an industry power and energy flow study and eventually for a development of product prototype. Challenges unique to this hybrid application, including the thermal system interface, drive cycle response, and battery management, are introduced. The system topology is presented, including the hybrid power architecture, electrical-thermal system specifications, and the integrated model operation and controls. The modeling approach for each electrical component, including ac machines, the battery set, and converters, is discussed. An average modeling technique is used because it models system-level power and efficiency over a long time interval with fast simulation. Battery simulation is improved from previous literature to provide a more accurate and robust solution. The model, interfaced with the thermal system, is verified by simulation studies in MATLAB/Simulink. A detailed model including transient response and harmonics gives a more accurate reading for power loss, at the cost of a slower simulation speed. It is not used directly for the industry study, but one detailed model is realized in Simulink/SimPowerSystems to validate the average model. The average model is also validated through experiments, including an active front end test, a battery test, and a variable speed ac motor drive test. Using the model, energy and cost-effectiveness are analyzed and discussed. Finally, the significance of the work is described and future improvements are suggested.
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I would also like to thank my graduate fellows Srikanthan Sridharan and Tutku Buyukdegirmenci, and our lab manager, Kevin Colravy, who helped me with theory development and the experimental set-up.

Last, I am most grateful to my mother, Rong Li, and my father, Tiechuan Cao, who have always supported and loved me.
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1 INTRODUCTION

1.1 Background

The development of hybrid technologies helps to reduce emissions and increase fuel economy in vehicles. In recent years, it has drawn researchers’ and industries’ attention to improve emissions and energy consumption issues from heavy duty trucks during idling. Many of the trucks are equipped with mobile refrigeration units (MRU) powered by auxiliary diesel engines. Figure 1.1 shows a typical produce delivery truck with an MRU. An airborne toxic and control measure (ATCM) regulation has been proposed for MRU diesel engines to reduce particulate matter (PM) emissions by 95% and nitrogen oxides (NO\textsubscript{x}) by 65% between 2004 and 2014 [1].

![Figure 1.1. A typical produce delivery truck with MRU](Source: FormerWMDriver on flickr.com)

An MRU is a refrigeration system controlling the temperature in a truck shipping container. It consists of a power unit which is usually a diesel engine, a refrigerant compressor, a throttling valve, an evaporator, a condenser, fans for circulating the air over the heat exchangers and a climate controller [2]. MRUs are used to deliver temperature sensitive products such as
frozen, fresh or perishable food, medications, etc., from warehouse to market, and are usually installed on midsize to large refrigerated trucks. The trucks can operate under a wide variety of driving conditions, including high-speed limited-access highways or low-speed local streets, mountainous terrains or flat country roads, and hot or cold ambient temperatures. Table 1.1 presents three possible scenarios. MRUs sometimes remain stationary for hours while loading and unloading. Temperature is maintained by on/off engine cycling and loading/unloading the MRU compressor.

Table 1.1. Delivery truck operating scenario examples

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles per day</td>
<td>300</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Stops per day</td>
<td>4</td>
<td>8-12</td>
<td>15-20</td>
</tr>
<tr>
<td>Length per stop (min)</td>
<td>25</td>
<td>15-20</td>
<td>10-15</td>
</tr>
<tr>
<td>Duration of doors open per stop (min)</td>
<td>10-15</td>
<td>5-10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Total length of maintained temperature required at stops (min)</td>
<td>40-60</td>
<td>80-200</td>
<td>100-250</td>
</tr>
</tbody>
</table>

Instead of trying to reduce emissions from the MRU diesel engine, it is preferred to eliminate this diesel engine and seek an alternative power source. Given current hybrid technology, this is possible. The compressor is driven by an electric machine, usually an ac machine, which is powered and controlled by an ac motor drive. Hybrid power is applied to this motor drive. There are a few considerations. MRUs must have sufficient refrigeration capacity to maintain the desired set-point temperature, meet the cooling load demand and have fast pull-down characteristics. Fast pull-down for a loaded truck is necessary to deal with frequent
opening and closing of the container door. The cooling capacity for a typical truck container varies between 3 and 9.3 kW [3]. When possible, MRUs can also have an option to plug in the grid such as at loading docks. Commercial chargers can have three-phase 208 V, rated 50 A, and up to 12 kW input power [4].

A hybrid power system requires power both from the truck’s main diesel engine and from at least one other energy storage device. The latter can be a battery, a hydrogen fuel cell, a super capacitor, etc., which supplies power to the motor drive and is also charged by the engine or from the grid when necessary. Batteries are safe and stable power sources, and are relatively inexpensive. However, they still face challenges such as the need for high energy density and quick recharging rates. Lead-acid, nickel-metal hydride, molten salt, and lithium-ion battery types can be used for transportation electrification purposes. Most electric vehicles (EVs), including the Nissan Leaf and Tesla Motors S, utilize lithium-ion batteries because they allow rapid charges as fast as a few minutes, and feature long life, fire resistance, and environmental friendliness [5].

Variable speed drives (VSD) have significant implications for the efficient use of energy for an MRU. Conventional unit-cycling and two-speed regulation methods for MRUs are inefficient at controlling refrigeration capacity. Frequent starting and stopping of the compressor leads to increasingly unsteady operation, high start-up power requirements, and high system maintenance [3]. As the refrigeration system capacity is proportional to the compressor speed, capacity control can be achieved by changing the compressor speed. Inverter based ac VSD are used in many commercial and residential applications to achieve better control and energy savings. However, in the MRU industry, diesel engine driven compressors still dominate, as shown in Figure 1.2, and there is little VSD market penetration [1].
A hybrid-powered thermal-enhanced system architecture is proposed in Figure 1.3. On the electrical engineering side, a hybrid power system model has been constructed utilizing a generator, battery, variable frequency ac motor drive, and power electronics technology. On the mechanical engineering side, an advanced controlled thermal system with thermal storage options has been modeled. The power system and thermal system models are interfaced at the ac machine and compressor junction. The combined model evaluates the hybridization system architecture and controls strategy in regard to expected cooling duty cycles. Model-based optimization criteria for performing control design tradeoffs, such as set-point maintenance vs. energy consumed, will be addressed.
Figure 1.3. Proposed hybrid-powered thermal-enhanced system architecture [6]
1.2 Motivation and Literature Review

As mentioned earlier in this chapter, preventing pollution while a truck is idling is a strong reason to use hybrid-powered MRUs. Because converting an MRU power system to hybrid requires extra hardware and labor cost, one needs other incentives to make this change. HEVs have proved to be more energy efficient than the conventional combustion engine vehicles [5]. One major energy-saving feature in HEVs is regenerative braking, meaning that the energy generated from vehicle deceleration is stored in batteries instead of being wasted as heat [7]. The stored energy is later used to power an electric motor for vehicle traction. However, in the MRU case, the compressor has no deceleration region, making the regenerative braking feature infeasible. Another energy saving point of interest is at diesel engine efficiencies. The medium to heavy-duty truck main diesel engine has a higher efficiency than the light-duty compressor diesel engine [8]. Becoming hybrid means that all the compressor energy comes from the main engine. However, it should be noted that the hybrid power system, including electric machines and power electronics that connect the truck engine and the compressor, is not lossless. Only if the truck engine is significantly more efficient than the compressor engine, and the hybrid power system is reasonably efficient itself, can the hybrid topology be an investment by industries and customers.

The hybrid power system efficiency for a typical MRU is unknown. The recommended approach is to model and simulate this system, and then to build a prototype for validation. Commercial simulators such as Autonomie are suggested in [9]. Although these simulators have well-refined component blocks for a hybrid power system, they are mostly used for HEV applications and lack the possibility to integrate with the thermal system of an MRU. In [10-11], recent development of VFDs in refrigeration systems is discussed. These papers describe
possible configurations for ac-grid powered systems as well as hybrid electric systems with ac
generators and batteries as the sources. Much emphasis has been placed on improvement for
controls to reduce total harmonic distortions and to improve efficiencies. A few also mention
industry standards and hardware implementation using VHDL/FPGA programmed digital signal
processors. However, few publications mention hybrid power systems for MRUs, particularly at
the system level and their modeling and simulation strategy. The differences between MRUs and
other refrigeration units include 1) frequent and drastic temperature changes due to loading and
unloading products, 2) variety of truck moving profiles depending on road conditions and
delivery schedules, and 3) availability of consistent and reliable power sources. Therefore, it is
necessary to build our own hybrid power system model in a suitable simulation tool and integrate
it with another thermal model that together can address the issues above. The models must be run
at the system level over extended periods of time because we are most interested in this hybrid
MRU topology’s practicality in the sense of system efficiency, and energy and cost savings.

In [12-14], various modeling and simulation methods for HEV power systems, including
machines and power electronics, are suggested. In particular, [15-18] provide modeling solutions
to lithium-ion batteries for hybrid electric systems. These electrical models are built in
MATLAB/Simulink, and the thermal model can be constructed in the same environment and
interfaced without extra effort. It should be noted that some of the modeling approaches are
intended for hardware design and include details such as machine transient dynamics and
semiconductor switching actions. As suggested by [19] these details in Simulink drastically
decrease the simulation speed and are not suitable for an efficiency study on a macro scope.
Hence the averaging modeling approaches solicited by [20] are necessary. With this philosophy
considered, electric machine steady-state equivalents by [21-22] and average loss calculation in
power semiconductors by [23] are implemented. In addition, a conversion from time-domain differential equations to frequency-domain transfer functions for lithium-ion battery modeling in [24-25] can be achieved. Therefore, a high-speed average model of hybrid power systems for MRUs is expected. Efficiency and energy flow for MRUs over a long period can be obtained and studied. Insightful energy and cost savings can be suggested to evaluate the hybrid system’s performance and assist in decisions on whether or not a future development effort towards such a system is meaningful.
1.3 Thesis Outline

This thesis is focused on system-level power and efficiency modeling based on fast simulation, integrated with the refrigeration thermal system. The approach is defined as the average model in subsequent chapters. A detailed dynamic model with transient analysis follows for validation purpose and is called the detailed model for short. The challenges lie in integrating the refrigeration system with an ac drive subsystem, responding to the dynamic drive cycle on the alternator side, and managing batteries for unexpected thermal loadings, depending on whether or not the truck is mobile. The average model can be easily integrated with the thermal system model, because its simulation speed is comparable to that of the thermal system model, and it is flexible to run at the user-desired time, power level, and drive cycle. It also provides a user-friendly interface for easy modification of system parameters.

An overview of the hybrid power system configuration is presented in Chapter 2. Details about the averaging modeling approaches are discussed in Chapter 3. In Chapter 4, power level and efficiency results of each model component are achieved through successful simulation based on reasonable assumptions as well as necessary machine, semiconductor device, and battery parameters. A comprehensive simulation, integrating the hybrid power system and the thermal system, is run against varying drive cycles and loading requirements. System dynamics, including harmonics and complex variables, in addition to power and efficiency performance, are also simulated from the detailed model. Chapter 5 describes the experimental set-up and objectives. Relevant experimental data are presented and demonstrate the model’s accuracy. Chapter 6 analyzes energy and cost-effectiveness using the average model for the MRU hybrid power system.
2 SYSTEM OVERVIEW

A broad system configuration of a proposed hybrid MRU is depicted in Figure 2.1, and a visualized system layout is shown in Figure 2.2. The system takes in power from the engine via a direct-coupled generator, and also has the option to connect to the grid. A pack of lithium-ion batteries also supplies power as a dc source. After power conversion and control, motor drives operate compressors, fans, and blowers, comprising the thermal system. Heaters are also needed to cover a full range of climate conditions. Figure 2.3 shows the hybrid power system: an engine shaft drives an ac generator feeding a rectifier with a stabilized output dc bus; then a dc-ac inverter connected to an ac induction machine drives the compressor; and the battery is in parallel and connects at the dc bus. Notice that a dc-dc boost converter is required after the rectifier because the rectifier output dc voltage is limited by the variable generator ac voltage. In most cases the rectifier dc voltage is 200-500 V.

Figure 2.1. System configuration of the proposed MRU
An ac machine rated up to 9 kW is selected based on previous industry experiences and the typical industry cooling capacity for a truck container suggested by [3]. A three-phase 12 HP 460 V 60 Hz Y-connected ac induction machine (IM) is chosen (actual model withheld for proprietary purpose). The machine can be configured as 230 V Y-connected; however, this
doubles the system current, which results in more losses and thermal issues related to the IGBTs and other electric components. An equivalently rated ac permanent magnet synchronous machine (PMSM) is also suitable as the motor. Given the ac machine ratings, a dc bus voltage of 700 V is deemed appropriate, and 1.2 kV IGBTs are suitable for all the power electronic devices. Energy from a battery pack flows through a dc-dc boost converter before being connected to the dc bus. The battery voltage can be in the 300-400 V range to maximize conversion efficiency. A three-phase 17.3 kVA PMSM is chosen as the generator to be coupled with the engine.

The system model is built in MATLAB/Simulink. The goal of this hybrid system model is to analyze long-term system and component response for practicality, hardware limitations, efficiency, and fuel cost. It is most important to observe the power and efficiency at each subsystem. Averaging and detailed modeling approaches are possible. For the average model, simulation is carried out at the system level over a long time interval but must run quickly. It simulates power changes and efficiency in equivalent steady-states at a fast simulation speed. The model tolerates a wide range of sampling times up to 0.1 s to accommodate different thermal or other electrical interfacing requirements. The detailed model is of higher-order dynamics that include additional details, such as voltage/current transients and harmonics. However, its simulation sampling time is a maximum 5 µs. For example, for a three-minute real-time simulation run, the average model is able to simulate one hour of the system performance, whereas the detailed model produces only two seconds of the model dynamics [20].

The average model strategy is chosen because it can be integrated with the thermal system model, which has time steps of a few ms, and it is flexible to run at user-desired times, power levels, and drive cycles. It also provides a user-friendly interface for easy modification of system parameters. The approach is to model power losses in each subsystem (motor, converter,
battery, etc.), including conduction and switching devices loses, based on equivalent steady-state conditions. Most losses have a direct relationship to the associated currents. Calculated output currents from one subsystem are passed as input currents to the next subsystem. The power flow can be examined in either direction, with input and output currents changing roles. For example, current flowing into the induction machine can be calculated, given the output speed and torque to the MRU compressor, and motor power loss can also be obtained. This induction machine current then becomes the inverter output current. Machine mechanical losses must also be included. These can be obtained from data sheets and basic tests.

A detailed dynamic model is still necessary and is constructed in Simulink/SimPowerSystems. It serves as a validation check for the average model and is helpful for future power electronic hardware design and implementation. The detailed model includes stepping waveforms at each switching action from the semiconductor devices, with consideration of snubber circuits. It also models the electric machines (PMSM, IM) as differential equations that produce transient waveforms. Filters are also included between components, and harmonics analysis can be performed.

Subsystem blocks shown in Figure 2.4 are based on the model structure in Figure 2.3. The subsystems in the left column represent the engine-powered compressor drive, and those on the upper right represent the battery powered compressor drive. Power level, battery state, and efficiency observation are shown in the scopes.
The model can run based on the following scenarios: 1) Engine on, compressor on, battery charging off; 2) engine on, compressor on, battery charging on; 3) engine on, compressor off, battery charging on; 4) engine on, compressor off, battery charging off; 5) battery on, compressor on; and 6) everything off. Notice that engine on and battery on are mutually exclusive events. Users can define a critical engine RPM above which the engine is treated as on. Similarly, the battery must be charged when the SOC (state of charge) is below a predefined value. Signals from the thermal system will indicate when the compressor should be on.

The MATLAB/Simulink model can be run from any arbitrary time in the drive cycle and can accept different initial states in each subsystem. It tolerates a wide range of sampling times up to 0.1 s to accommodate different thermal or other electrical interfacing requirements.
3 MODELING APPROACHES

3.1 Drive Cycle

A delivery truck with the MRU can operate under a variety of driving conditions including various speeds and run/stop times, etc., as mentioned in Chapter 1. It is necessary to model a hypothetical drive cycle so that it can represent a typical delivery day. A daily delivery schedule, as shown in Table 3.1, is provided by [26].

Table 3.1 Proposed daily delivery schedule and truck condition

<table>
<thead>
<tr>
<th>Time</th>
<th>Duration (min)</th>
<th>Condition</th>
<th>Time</th>
<th>Duration (min)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:30</td>
<td>15</td>
<td>Truck traveling</td>
<td>12:39</td>
<td>1</td>
<td>Door opened</td>
</tr>
<tr>
<td>6:45</td>
<td>7</td>
<td>Truck stopped, engine off, door opened</td>
<td>12:40</td>
<td>10</td>
<td>Door closed, truck traveling</td>
</tr>
<tr>
<td>6:52</td>
<td>64</td>
<td>Door closed</td>
<td>12:50</td>
<td>6</td>
<td>Truck stopped, engine off, door opened</td>
</tr>
<tr>
<td>7:56</td>
<td>15</td>
<td>Truck traveling</td>
<td>12:56</td>
<td>54</td>
<td>Door closed</td>
</tr>
<tr>
<td>8:11</td>
<td>7</td>
<td>Truck stopped, engine off, door opened</td>
<td>13:50</td>
<td>1</td>
<td>Door opened</td>
</tr>
<tr>
<td>8:18</td>
<td>64</td>
<td>Door closed</td>
<td>13:51</td>
<td>15</td>
<td>Door closed, truck traveling</td>
</tr>
<tr>
<td>9:22</td>
<td>15</td>
<td>Truck traveling</td>
<td>14:06</td>
<td>6</td>
<td>Truck stopped, engine off, door opened</td>
</tr>
<tr>
<td>9:37</td>
<td>6</td>
<td>Truck stopped, engine off, door opened</td>
<td>14:12</td>
<td>58</td>
<td>Door closed</td>
</tr>
<tr>
<td>9:43</td>
<td>64</td>
<td>Door closed</td>
<td>15:10</td>
<td>1</td>
<td>Door opened</td>
</tr>
<tr>
<td>10:47</td>
<td>1</td>
<td>Door opened</td>
<td>15:11</td>
<td>15</td>
<td>Door closed, truck traveling</td>
</tr>
<tr>
<td>10:48</td>
<td>15</td>
<td>Door closed, truck traveling</td>
<td>15:26</td>
<td>6</td>
<td>Truck stopped, engine off, door opened</td>
</tr>
<tr>
<td>11:03</td>
<td>6</td>
<td>Truck stopped, engine off, door opened</td>
<td>15:32</td>
<td>59</td>
<td>Door closed</td>
</tr>
<tr>
<td>11:09</td>
<td>65</td>
<td>Door closed</td>
<td>16:31</td>
<td>1</td>
<td>Door opened</td>
</tr>
<tr>
<td>12:14</td>
<td>1</td>
<td>Door opened</td>
<td>16:32</td>
<td>0</td>
<td>Door closed</td>
</tr>
<tr>
<td>12:15</td>
<td>24</td>
<td>Door closed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The truck leaves the dispatch center at 6:30 in the morning and returns at 4:32 in the afternoon. While the truck is running, it is commuting between delivery stations. After the truck reaches a delivery location, the container door is opened to unload or load goods, and then closed. It is important to maintain a required temperature inside the container. The door opening and closing event has a drastic impact on the internal temperature. This sudden cooling cycle change can impose an immediate high power demand from the electric system. During modeling and simulation, the thermal system demand is reflected in the increase of compressor speed and torque. The IM and the rest of the electric system must respond quickly to the change, and hence generate new power and efficiency profiles.

When the truck engine is running, it has varying power takeoff (PTO) speeds, with a minimum of 700 RPM and a maximum of 2450 RPM [8]. The electric generator, direct-coupled with the truck engine, has a pulley ratio of 2.06, and therefore, the minimum generator RPM is 1442 and maximum is 5047. Table 3.2 presents two simple hypothetical cases of how the engine PTO speeds vary during delivery condition associated with Table 3.1. Figure 3.1 is the graph depicting the data in Table 3.2.

The above cases give an idea what a drive cycle behaves like, but they are far less sophisticated and realistic. Drive cycle data from actual driving conditions are found from an industry vehicle battery validation study [27]. For the study, a test vehicle was run through several drive cycles to gather actual RPM, temperature, and battery current and voltage data to compare to the simulation. Figure 3.2 shows the first 20 minutes of the drive cycle after adjusting the original data scales for both RPM’s and times. The truck engine speed varies during the first 15 minutes, and stops while the door is open. The same dynamic is repeated throughout the rest of the day, as shown in Figure 3.3. The drive cycle profile directly guides the generator running
speed by the pulley ratio, and determines the voltage and power from the generator to the rest of the electric system.

Table 3.2 Two simple engine RPM profiles for the day

<table>
<thead>
<tr>
<th>Time</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Time</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Time</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:30</td>
<td>700</td>
<td>700</td>
<td>6:41</td>
<td>2450</td>
<td>700</td>
<td>6:52</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:31</td>
<td>2450</td>
<td>2450</td>
<td>6:42</td>
<td>2450</td>
<td>700</td>
<td>6:53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:32</td>
<td>2450</td>
<td>2450</td>
<td>6:43</td>
<td>2450</td>
<td>2450</td>
<td>6:54</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:33</td>
<td>2450</td>
<td>700</td>
<td>6:44</td>
<td>2450</td>
<td>2450</td>
<td>6:55</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:34</td>
<td>2450</td>
<td>700</td>
<td>6:45</td>
<td>700</td>
<td>700</td>
<td>6:56</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:35</td>
<td>2450</td>
<td>2450</td>
<td>6:46</td>
<td>0</td>
<td>0</td>
<td>6:57</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:36</td>
<td>2450</td>
<td>2450</td>
<td>6:47</td>
<td>0</td>
<td>0</td>
<td>6:58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:37</td>
<td>2450</td>
<td>700</td>
<td>6:48</td>
<td>0</td>
<td>0</td>
<td>6:59</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:38</td>
<td>2450</td>
<td>700</td>
<td>6:49</td>
<td>0</td>
<td>0</td>
<td>7:00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6:39</td>
<td>2450</td>
<td>2450</td>
<td>6:50</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:40</td>
<td>2450</td>
<td>2450</td>
<td>6:51</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.1. Engine RPMs for cases in Table 3.2
Figure 3.2. Realistic engine RPMs for the first 20 min [8]

Figure 3.3. Realistic engine RPMs for a day [8]
3.2 Induction Machine

3.2.1 Induction machine power analysis

The IM is the direct interface with the thermal system. It is coupled with the compressor and responds to the thermal system speed and torque demands. Not only is the IM power analysis important, but also the IM control is crucial to respond robustly and efficiently.

For efficiency performance, to calculate the losses inside the machine, we first find the required output power and calculate the input voltage, current, and power factor, which lead to the total input power. The output power follows equation

\[ P_{IM\_out} = \omega \cdot T \]  

with the rotational speed and torque desired by the thermal system. There is a 1.6 pulley ratio between the IM and the compressor. Note that the mechanical loss between the power and thermal systems is not included, as there is no readily data available.

Circuit analysis must be performed for each phase of the IM in order to find the input voltage, current, and power factor. Assuming the IM is three-phase balanced, the per-phase equivalent steady-state circuit can be used as in Figure 3.4 [21]. The power flow is based on one phase of the IM.

![Figure 3.4. Equivalent steady state per phase circuit model of IM](image-url)

\[ P_{IM\_out} = \omega \cdot T \]  

(3.1)
The rotor series branch current is calculated based on

\[ P_{BM\text{,out}} = 3I_2^2R_2 \frac{1-s}{s} \]  \hspace{1cm} (3.2)

\[ I_2 = \sqrt{\frac{P_{BM\text{,out}}}{3R_2}} \frac{s}{1-s} \]  \hspace{1cm} (3.3)

where \( s \) is the machine slip. The slip calculation will be discussed more in Section 3.2.2. \( I_2 \) is the RMS current magnitude in the rotor branch. Taking this current as the reference, \( I_2 \) has an angle equal to zero. Hence the voltage across the shunt branch is

\[ V_2 \angle \delta_2 = I_2 \angle 0^\circ \cdot (R_2 - \frac{1}{s} + j2\pi I_2) \]  \hspace{1cm} (3.4)

The current flowing through the shunt branch can be calculated as

\[ I_m \angle \delta_m = \frac{V_2 \angle \delta_2}{j2\pi I_m} + \frac{V_2 \angle \delta_2}{R_1} \]  \hspace{1cm} (3.5)

Therefore, the current flowing through the stator series branch, or the IM input current, can be calculated as

\[ I_1 \angle \delta_{1I} = I_m \angle \delta_m + I_2 \angle 0^\circ \]  \hspace{1cm} (3.6)

Hence the total per-phase input voltage across the IM is

\[ V_1 \angle \delta_W = I_1 \angle \delta_{1I} \cdot (R_1 + j2\pi L_1) + V_2 \angle \delta_2 \]  \hspace{1cm} (3.7)
Finally, with the per-phase input voltage and current, the total three-phase input power can be calculated in equation

$$P_{IM} = 3\text{Re}(V_1 \angle \delta_W \cdot I_1 \angle -\delta_I)$$  \hspace{1cm} (3.8)

3.2.2 Induction machine control

The IM is to be controlled by the VSD methodology. The advantages of VSD ac motor drives include reduced energy consumption, smooth transient voltage and current waveforms, and little maintenance with long equipment life. Most commonly offered VSD control techniques are volts-per-hertz (V/f) control, field oriented control, direct torque control, etc. Each has its pros and cons. For this mobile refrigeration application, given that the IM is driving the compressor to maintain a certain range of thermal flow inside the truck storage body, no complicated and precise control is necessary, and the reduction of production cost is relatively more important. In this sense, a V/f control is chosen [22]. Figure 3.5 illustrates this control technique.

![Figure 3.5. IM V/f control diagram](image-url)
The inputs are speed and torque references from the thermal system. The outputs are controlled stator voltage, input frequency, and slip. The stator voltage and slip can be expressed in terms of the frequency, as shown in equations

\[
\frac{V_{\text{stator}}}{f} = \frac{460/\sqrt{3}}{60} \quad \text{or} \quad V_{\text{stator}} = \frac{460/\sqrt{3}}{60} f \quad (3.9)
\]

\[
s = 1 - \frac{n_{\text{ref}}}{n_{\text{sync}}} = 1 - \frac{n_{\text{ref}}}{120f / p} \quad \text{or} \quad f = \frac{n_{\text{ref}} p}{120(1 - s)} \quad (3.10)
\]

where \( f \) is the frequency in Hz, \( p \) is the number of poles, and \( s \) is the slip. The slip calculation subsystem which implements the Simulink built-in algebraic constraint block essentially solves

\[
T_{\text{calc}} - T_{\text{ref}} = 0 \quad (3.11)
\]

where \( T_{\text{calc}} \) is the calculated torque based on an initial slip estimate, usually about 0.02, and \( T_{\text{ref}} \) is the desired torque output. The algebraic constraint block produces the slip by forcing the two torque values to be equal via feedback PI control. Then the input frequency and voltage values are eventually known from (3.9) and (3.10). The calculated torque is based on

\[
T_{\text{calc}} = \frac{3I_z^2 (R_2 / s)}{\omega_s} \quad (3.12)
\]

which is the same as

\[
T_{\text{calc}} = \frac{3(R_2 / s)}{\omega_s} \left( \frac{V_{\text{eq}}^2}{(R_{\text{eq}} + (R_2 / s))^2 + (X_{\text{eq}} + X_2)^2} \right) \quad (3.13)
\]
in which \( I_2 \) is replaced by a series of calculation using the Thevenin equivalent circuit from Figure 3.4, and \( \omega_s \) is the synchronous speed in rad/sec. \( V_{eq}, R_{eq}, \) and \( X_{eq} \) are solved by [21]

\[
V_{eq} = V_{stator} \left| \frac{(jX_m \parallel R_c)}{(jX_m \parallel R_c) + (R_i + jX_i)} \right| \quad (3.14)
\]

\[
R_{eq} + jX_{eq} = Z_{eq} = \frac{(jX_m \parallel R_c)(R_i + jX_i)}{(jX_m \parallel R_c) + (R_i + jX_i)} \quad (3.15)
\]

A quick check to see if the system works is to verify if the \( V_{stator} \) value (3.9) and \( V_1 \) value (3.7) in the IM system are equal.

### 3.2.3 Induction machine parameters calculation

In industry, engineers are usually provided with machine data sheets, which include the following values: rated voltage, rated frequency, locked rotor current, locked rotor torque, number of poles, power factor at rated frequency, efficiency at rated frequency, rated horse power at rated frequency, and rated RPM at rated frequency. These data sheets can be used to derive the equivalent stator/rotor resistance \( (R_1, R_2) \) and leakage inductance \( (L_1, L_2) \) as well as copper resistance \( (R_c) \) and magnetizing inductance \( (X_m) \), given the IM per-phase equivalent circuit (Figure 3.4).

The impedances, at two different frequencies, given in

\[
|Z_{f1}| = |(R_1 + R_2) + j2\pi f_1(L_1 + L_2)| \quad (3.16)
\]
\[ |Z_{f2}| = |(R_1 + R_2) + j2\pi f'_2(L_1 + L_2)| \] (3.17)

can be found from the locked rotor test in

\[ |Z_f| = \frac{V_{\text{rated}}}{\sqrt{3} I_{\text{locked}}} \] (3.18)

Then \( L_1 \) and \( L_2 \) can be found from equation

\[ L_1 = L_2 = \frac{1}{2}(L_1 + L_2) = \frac{1}{2} \sqrt{\frac{Z_{f1}^2 - Z_{f2}^2}{(2\pi f'_1)^2 - (2\pi f'_2)^2}} \] (3.19)

where \( L_1 \) and \( L_2 \) are assumed to be equal. The rotor resistance \( R_2 \) can be measured from a locked rotor test when slip \( s \) is equal to 1. Equation

\[ P = 3I_{\text{locked}}^2 R_2 \frac{1}{s} \] (3.20)

defines the air gap power, and equation

\[ T = 3I_{\text{locked}}^2 R_2 \frac{1}{s} / [(2\pi f'_1) / \text{pole}] \] \[ /2 \] (3.21)

defines the torque from (3.20) [21]. The locked torque is given in the data sheets. \( R_1 \) then can be found from a derivation of (3.16) or (3.17).

Now we will determine \( R_c \) and \( L_m \) in the shunt branch. The main idea is to find the impedance of \( R_c \) and \( L_m \), or actually easier, the admittance. The admittance can be found if the shunt branch voltage and current are known. Shunt voltage can be realized from equations
\[ V_{\text{shunt}} = \frac{V_{\text{rated}}}{\sqrt{3}} - I_1 (R_1 + j2\pi f L_1) \]  
(3.22)

\[ I_1 = |I_1| \delta = \frac{746 \cdot HP/eff/PF/3}{V_{\text{rated}}/\sqrt{3}} \angle - \arccos(PF) \]  
(3.23)

Shunt current can be realized from

\[ I_{\text{shunt}} = I_1 - I_2 = I_1 - \frac{V_{\text{shunt}}}{R_2/s + j2\pi f L_2} \]  
(3.24)

\[ L_m \text{ and } R_c \text{ are found from} \]

\[ Y_{\text{shunt}} = I_{\text{shunt}}/V_{\text{shunt}} = \frac{1}{R_c} + \frac{1}{j2\pi f L_m} \]  
(3.25)

The IM datasheet and the MATLAB code for the machine parameter calculation are in the appendix.
3.3 Power Electronics Loss Modeling

3.3.1 Inverter

The inverter power losses can be found once the induction machine input power \( P_{IM} \) and line currents \( I_{rms,IM} \) are calculated. The total inverter loss consists of conduction and switching losses in IGBTs.

![Figure 3.6. dc-ac inverter circuit diagram](image)

The dc-ac inverter is modeled as three-phase full H-bridge with 6 IGBTs, as shown in Figure 3.6. The conduction loss is incurred when the IGBT is turned on. It can be modeled as an ideal switch in series with a forward voltage drop \( V_{on} \) and a series resistor \( R_{ds} \), as shown in Figure 3.7. \( V_{on} \) and \( R_{ds} \) can be obtained directly from the IGBT datasheet. For this project, 1.2 kV IGBTs are chosen.

![Figure 3.7. Circuit model of a semiconductor device](image)
The average conduction loss per IGBT pair is calculated in equation [23]

\[ P_{on\_inv} = \frac{2\sqrt{2}I_{rms\_im}V_{on}}{\pi} + I_{rms\_im}^2 R_{ds} \]  

(3.26)

and then multiplied by three for a three-phase circuit. The average switching loss of each IGBT pair is calculated by [23]

\[ P_{switch\_inv} = \frac{2\sqrt{2}I_{rms\_im}V_{bus}}{\pi} f_{switch\_inv} \frac{t_{on} + t_{off}}{2} \]  

(3.27)

where \( f_{switch\_inv} \) is the 10 kHz inverter switching frequency. Times \( t_{on} \) and \( t_{off} \) are the switching rise and fall times, respectively, which are also found in device datasheet. \( V_{bus} \) is the 700 V main dc bus voltage. The loss again is multiplied by three for a three-phase circuit.

Thus, the total power into the dc-ac inverter is summarized in

\[ P_{inv} = P_{BM} + 3P_{on\_inv} + 3P_{switch\_inv} \]  

(3.28)

3.3.2 Converter

A dc-dc converter is used between the rectifier and the dc bus, and one is also used between the battery and the dc bus. The modeling approach is the same for both converters. A boost converter between the rectifier and the dc bus is shown in Figure 3.8. The power loss consists of the IGBT and diode conduction losses and the IGBT switching losses.

The converter duty ratio must be known to find the losses. It is calculated based on
where $V_{out\_conv}$ is 700 V, the same as the dc bus voltage, and $V_{in\_conv}$ is the dc voltage to be computed in Section 3.3.3 from the rectifier ($V_{out\_rect}$). The rearrangement of terms in (3.29) simplifies some Simulink work. A lower limit is set for $V_{in\_conv}$ so that if the input voltage is too low, the duty cycle is set to be zero.

![Boost converter circuit diagram](image)

**Fig. 3.8. Boost converter circuit diagram**

The converter conduction loss, like the inverter conduction loss, can be modeled using Figure 3.7 (Section 3.3.1). It is based on

$$P_{on\_IGBT\_conv} = DI_{L\_conv}V_{on} + DI_{L\_conv}^2R_{ds}$$

where $I_{L\_conv}$ is the converter input current, $D$ is the duty cycle, $V_{on}$ is the IGBT forward voltage, and $R_{ds}$ is the IGBT series resistance. Given $V_{in\_conv}$, $I_{L\_conv}$ is calculated after $P_{conv}$, the total converter input power, is found with all the losses included. This may create a potential algebraic loop in Simulink, since $I_{L\_conv}$ is also required to calculate $P_{in\_conv}$. To avoid this, a sampling delay time is inserted in Simulink for the $I_{L\_conv}$ calculation. The diode conduction loss is similar except that the diode is turned on during the $I\_D$ cycle, and it is only modeled as a forward voltage drop in series with an ideal switch, as shown in
\[ P_{\text{on,DiodeConv}} = (1 - D) I_{\text{L,conv}} V_{\text{on,diode}} \]  

(3.31)

The average IGBT switching loss is found using equation [23]

\[ P_{\text{switch,conv}} = f_{\text{switch,conv}} \left( \frac{t_{\text{on}} + t_{\text{off}}}{2} \right) V_{\text{out,conv}} D I_{\text{L,conv}} \]  

(3.32)

where \( f_{\text{switch,conv}} \) is the 10 kHz switching frequency, \( t_{\text{on}} \) and \( t_{\text{off}} \) are the switching rise and fall times in the device, and \( V_{\text{out,conv}} \) is the same as the main dc bus voltage.

Therefore, the total power into the dc-dc converter is summarized in

\[ P_{\text{conv}} = P_{\text{inv}} + P_{\text{batt}} + P_{\text{on,IGBTConv}} + P_{\text{on,DiodeConv}} + P_{\text{switch,conv}} \]  

(3.33)

where \( P_{\text{inv}} \) and \( P_{\text{batt}} \) are the power flowing to the dc-ac inverter and battery charger, respectively.

3.3.3 Rectifier

The ac-dc rectifier topology is like the dc-ac inverter, but flipped horizontally, as shown in Figure 3.9. Hence the power loss calculation is similar. The average conduction loss per IGBT switch pair is shown in equation [23]

\[ P_{\text{on,rect}} = \frac{2\sqrt{2} I_{a,PMSM} V_{\text{m}}}{\pi} + I_{a,PMSM}^2 R_{ds} \]  

(3.34)

where \( I_{a,PMSM} \) is the line RMS current out of the PMSM ac generator. \( I_{a,PMSM} \) is calculated in Section 3.4.
The average switching loss of each IGBT switch pair is found using [23]

\[
P_{\text{switch rect}} = \frac{2\sqrt{2} I_{\text{a PMSM}} V_{\text{out rect}}}{\pi} f_{\text{switch rect}} \frac{t_{\text{on}} + t_{\text{off}}}{2}
\]  

(3.35)

where \(f_{\text{switch rect}}\) is the 10 kHz switching frequency, and \(V_{\text{out rect}}\) is the rectified output dc voltage. \(V_{\text{out rect}}\) can be controlled to vary up to the maximum, which is limited by the generator line-line voltage. Given the generator voltage range in Table 3.3 in Section 3.4, it is reasonable for this average model to fix \(V_{\text{out rect}}\) at a particular value, as in equation

\[
V_{\text{out rect}} = \sqrt{2} \sqrt{3} \frac{3}{\pi} V_{\text{t PMSM}}
\]  

(3.36)

based on a passive rectifier topology, which is only directly proportional to the PMSM terminal voltage [23]. Under typical drive cycle \(V_{\text{out rect}}\) yields an efficient 200-500 V for the boost converter input voltage, knowing that the converter output voltage is 700 V dc bus.

Therefore, the total power going into the ac-dc rectifier is summarized in

\[
P_{\text{rect}} = P_{\text{conv}} + 3P_{\text{on rect}} + 3P_{\text{switch rect}}
\]  

(3.37)
3.4 Generator

The generator takes in power from the mechanically coupled truck engine and sends it to the rectifier, as shown in Figure 2.3. It is modeled as a PMSM, and a particular 17.3 kVA machine is chosen. The power loss consists of generator winding losses and mechanical losses between the engine and generator.

In order to find the machine winding losses, the current through each generator phase must be calculated from equations

\[
P_{1\phi} = \frac{E_a V_{t_{PMSM}} \sin \delta}{2\pi f L_s}
\]

\[
\Rightarrow \delta = \sin^{-1} \left( \frac{2\pi f L_s P_{1\phi}}{E_a V_{t_{PMSM}}} \right)
\]

\[
\frac{E_a \angle \delta - V_{t_{PMSM}} \angle 0}{R_a + j2\pi f L_s} = I_{a_{PMSM}} \angle \varphi
\]

which are based on PMSM per-phase equivalent circuit is shown in Figure 3.10 [21]. The ac source represents line-neutral armature RMS voltage, \( R_a \) the armature resistance, and \( X_s \) (or \( 2\pi f L_s \)) the synchronous reactance.

![Figure 3.10. PMSM per-phase equivalent circuit diagram](image)
$P_{1φ}$ is the per-phase output power, which is one third of the known power into the rectifier, $P_{\text{rect}}$.

$E_a$ is the armature voltage (line-neutral RMS) calculated by

$$E_a = k\omega$$

where $k$ is a constant and $\omega$ is the rotational speed in thousands RPM.

Table 3.3. Data sheet for a selected PMSM

<table>
<thead>
<tr>
<th>Alternator Speed (RPM)</th>
<th>Output frequency (Hz)</th>
<th>Maximum No load voltage @ -40°C (V)</th>
<th>Maximum No load voltage @ +20°C (V)</th>
<th>Minimum full load voltage @ 20°C on pure resistive load (V)</th>
<th>Output power (kVA)</th>
<th>No load losses (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>100</td>
<td>201</td>
<td>195</td>
<td>138</td>
<td>8.7</td>
<td>150</td>
</tr>
<tr>
<td>1875</td>
<td>125</td>
<td>251</td>
<td>244</td>
<td>176</td>
<td>10.8</td>
<td>200</td>
</tr>
<tr>
<td>2250</td>
<td>150</td>
<td>302</td>
<td>293</td>
<td>213</td>
<td>13.0</td>
<td>250</td>
</tr>
<tr>
<td>3000</td>
<td>200</td>
<td>402</td>
<td>390</td>
<td>286</td>
<td>17.3</td>
<td>500</td>
</tr>
<tr>
<td>4500</td>
<td>300</td>
<td>603</td>
<td>585</td>
<td>476</td>
<td>17.3</td>
<td>1100</td>
</tr>
<tr>
<td>5500</td>
<td>334</td>
<td>670</td>
<td>650</td>
<td>535</td>
<td>17.3</td>
<td>1300</td>
</tr>
<tr>
<td>5600</td>
<td>375</td>
<td>750</td>
<td>728</td>
<td>605</td>
<td>17.3</td>
<td>2200</td>
</tr>
<tr>
<td>6000</td>
<td>400</td>
<td>804</td>
<td>780</td>
<td>651</td>
<td>17.3</td>
<td>2900</td>
</tr>
<tr>
<td>9000</td>
<td>600</td>
<td>1206</td>
<td>1170</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The generator RPM value is directly proportional to the drive-cycle controlled engine RPM, with a 2.06 pulley ratio. $k$, in volts (line-neutral RMS) per 1000 RPM, is realized by dividing the fourth column in by the first column in Table 3.3, a testing datasheet for a selected PMSM (actual machine model withheld for proprietary purpose). The relationship between these two columns is linear. Note that the values in column 4 are in line-line RMS, which is $\sqrt{3}$ times the line-neutral RMS. Due to engine RPM limit, generator speeds are only used up to 5000 RPM.

It is reasonable to assume that the terminal voltage magnitude ($V_{l,PMSM}$) is the same as the armature voltage magnitude ($E_a$), but the phase angles are different. The PMSM frequency, $f$, can be calculated by a frequency constant multiplied by the rotational speed; the relationship is linear.
The frequency constant, in Hz per 1000 RPM, is realized from columns 1 and 2 of Table 3.3. $R_a$ and $L_s$ are obtained from simple machine tests, and they are 0.5 $\Omega$ and 2 mH, respectively. The current magnitude is only required for power loss calculation, as shown in

$$P_{loss\_PMSM} = 3I_{a\_PMSM}^2R_a$$ (3.41)

In which the current angle, $\varphi$, is not used.

There is another loss in the system, mechanical loss, which is represented in the last column of Table 3.3. It is interpolated as a quadratic function of RPM. This function is shown in

$$P_{mech\_PMSM} = 5.0459 \times 10^{-5} RPM^2 + 0.011022 RPM$$ (3.42)

which has a 0.99 coefficient of determination ($R^2$).

Therefore, the total generator input power is summarized in

$$P_{PMWM} = P_{rect} + P_{loss\_PMSM} + P_{mech\_PMSM}$$ (3.43)

Note that this power is also the overall system input power.
3.5 Battery

The battery model is the key to the hybrid power system. An accurate and efficient model is required to estimate battery instantaneous conditions and to interface properly with other models in the power system. The battery model consists of four blocks, *Battery Cell*, *SOC*, *Battery Power Loss*, and *Power Battery*. They calculate individual battery cell voltages, instantaneous state of charge (SOC) in each battery cell, instantaneous power losses through all the battery cells as well as total energy losses throughout a simulation cycle, and total power into/out of all the battery cells, respectively. An additional block controls the battery (dis)charge rate, based on running conditions in the overall system. The completed battery model enables a user to pre-program a critical charging SOC value, a desired charging current, numbers of parallel and series connected battery cells. Note that the battery models for the discharging stage and the charging stage are built separately. The principle is the same, but the parameters are mostly different.

The *Battery Cell* block is modeled as the circuit in Figure 3.1 [24]. The second, minute, and hour based resistors and capacitors predict battery cell behavior in each of the corresponding time frames. The terminal voltage is calculated in

\[
V_i = V_{oc} - I_c (R_{series} + R_{th} || \left( \frac{1}{sC_{ts}} + R_{tm} \right) || \left( \frac{1}{sC_{tm}} + R_{th} || \frac{1}{sC_{th}} \right))
\]  

(3.44)

Each parallel RC pair equivalent impedance is calculated in

\[
R \parallel \frac{1}{sC} = \frac{R/sC}{R+1/sC} = \frac{R/s}{RC+1/s}
\]  

(3.45)

34
The rearrangement of equations in (3.45) simplifies the block construction in Simulink. The modeling technique in [25] uses differential equations in the time domain. However, the frequency domain method used in (3.44) proves to be equally functional and more efficient.

The voltage source, resistors, and capacitors depend non-linearly on the battery SOC. In [24], $V$, $C$, and $R$ values are modeled as $6^{th}$ order polynomials of SOC. Upon simulation using the parameters from [25], some polynomial curves can become negative, which creates instability. Also the coefficients of determination ($R^2$) of the $6^{th}$ order polynomials with respect to the measured samples are poor (Figure 3.12). In [15], it suggests various ways to curve fit data points for battery modeling. In the proposed interpolation equations

$$\ln(V,C,R) = a_0 + a_1 \ln(SOC) + a_2 \ln^2(SOC) + ... + a_6 \ln^6(SOC) = \sum_{k=0}^{6} a_k \ln^k(SOC)$$

$$V,C,R = \exp\left(\sum_{k=0}^{6} a_k \ln^k(SOC)\right)$$

$R^2$ is a minimum of 0.8. One fitting curve is also plotted in Figure 3.12 to compare with the original curve. The new method produces more accurate $V$, $C$, $R$ values and thereby models the battery more robustly.

Figure 3.11. Electrical battery model circuit
The new coefficients of (3.46) are listed in Table 3.4. (C) and (D) indicate the coefficients for the charging and the discharging stages, respectively. Single-cell data (current, SOC) are extracted from precise measurements of Panasonic CGR18650A 3.7 V, 2200 mAh Li-
ion batteries [25]. The same curve fitting strategy can be applied to other battery types. Second, minute, and hour constants are tested with respect to SOC, and details regarding the testing are found in [25].

The SOC block is modeled based on

\[
SOC(t) = SOC_{initial} + \int_{0}^{t} f_1[i_{charge}(t)] \times i_{charge}(t) dt + \int_{0}^{t} f_2[i_{discharge}(t)] \times i_{discharge}(t) dt \tag{3.48}
\]

where the initial SOC is constant and defined prior to simulation, \(i(t)\) is the instantaneous discharging or charging current through each battery cell, and \(f\) is a function of that current and modeled as a 1-D lookup table. The relationships between \(f\) and \(i\) are given in Tables 3.5 and 3.6 for the charging and discharging stages [25]. The SOC function (3.48) is a combination of mentioned equations in [24]. The advantage is to reduce control effort and improve system monitoring.

Table 3.5. \(f\) and \(i\) relationship for the charging stage.

<table>
<thead>
<tr>
<th>(i) (charge)</th>
<th>0</th>
<th>0.0838</th>
<th>0.4386</th>
<th>1.0988</th>
<th>2.202</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f(i))</td>
<td>1.34\times10^{-4}</td>
<td>1.3259\times10^{-4}</td>
<td>1.2581\times10^{-4}</td>
<td>1.2391\times10^{-4}</td>
<td>1.2192\times10^{-4}</td>
</tr>
</tbody>
</table>

Table 3.6. \(f\) and \(i\) relationship for the discharging stage.

<table>
<thead>
<tr>
<th>(i) (discharge)</th>
<th>0</th>
<th>0.0808</th>
<th>0.4389</th>
<th>1.0886</th>
<th>2.1603</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f(i))</td>
<td>-1.4\times10^{-4}</td>
<td>-1.3751\times10^{-4}</td>
<td>-1.2727\times10^{-4}</td>
<td>-1.3222\times10^{-4}</td>
<td>-1.3928\times10^{-4}</td>
</tr>
</tbody>
</table>
Following the circuit diagram in Figure 3.11, the Battery Power Loss block is straightforward, as the power loss through $R_{series}$ is $I^2R$, and losses through $R_s$, $R_m$, $R_h$, are $V^2/R$. The sum of power losses in each cell is the battery package power loss. Total energy loss is the integration of all the power losses.

The charging power in the Power Battery block is the terminal voltage multiplied by the branch current, $VI$, then multiplied by the total number of cells. Note that for the discharging stage the total power consuming from the battery pack is this terminal power plus the total power loss as calculated in the Battery Power Loss block, as the current is going outwards.

Dc-dc converters are required between the battery package and the system main dc bus. These converter models are similar to those discussed earlier in the Section 3.3.2. Note that the discharging stage converter is a boost converter, and the charging stage a buck converter. One difference between the battery converter models is the duty cycle calculation. For the boost converter, it is $(1 - V_{battery}/V_{dc\_bus})$, and for the buck converter $V_{battery}/V_{dc\_bus}$. 
4 SIMULATION RESULTS

A comprehensive simulation must be run for the integrated thermal-electrical system. It is important to evaluate each electrical component’s performance under a real-life scenario. The scenario includes both the run/stop drive cycle as described in Section 3.1, and the dynamic thermal loading demand based on the desired truck container temperature, ambient temperature, door open/close events, etc. Figure 4.1 illustrates the system architecture. The power system model is commanded by the engine RPM that is tied to the generator (PMSM), and is controlled by the torque and speed references from the thermal system. The thermal system model receives power from the motor (IM) and supplies required cooling/heating capacity in the form of discharged air to the box (container) model, after compressing the returned air from the container.

Figure 4.1. MRU thermal-electric architecture for simulation integration
4.1 Average Model Simulation

The integrated system is simulated from 20,000 s to 29,000 s, which corresponds to 1:00 PM to 3:30 PM of the delivery schedule in Table 3.1. Figure 4.2 shows the engine and generator RPMs and serves as the drive cycle reference. There are several noteworthy events: container door opens (Figure 4.3), motor drives the compressor (Figure 4.4), and battery is charged and discharged (Figure 4.5). In these figures, “1” means the described event happens, and “0” means it does not. The door opening event is proposed in Table 3.1. The motor is operated when there is an enabling demand from the thermal system. The battery is charged, if below a preset SOC value, when the generator runs, and it is discharged when the motor is on while the truck is not moving.

Figure 4.2. Simulated engine and generator RPMs
In Figure 4.6, the truck delivers products under a proposed ambient temperature profile. The products require a temperature maintained between -30 °C and -25 °C. The thermal system then sends torque and speed references to the power system for the motor drive control, as shown in Figures 4.7 and 4.8. The motor RPM is between 1760 and 1785.
Figure 4.6. Ambient temperature change from 1:00 PM to 3:30 PM

Figure 4.7. Torque demand from the thermal system
The power profiles of different electrical components are obtained under the aforementioned conditions. In Figure 4.9, the power levels for the active front end, i.e., from the generator to the dc bus, are plotted. This part of the power system is turned on only when the truck engine is on. Notice that for both of these two active periods, the battery is charged all the time, but the motor runs during the first half period, as commanded by the thermal system. In a similar fashion, the inverter/motor and the battery charging/discharging powers are plotted in Figure 4.10 and Figure 4.11, respectively.
Figure 4.9. Power levels at the front end

Figure 4.10. Power levels at the ac drive
Given the power levels obtained from the above simulation, some efficiency curves are defined and plotted. In Figure 4.12, the engine power supply efficiency is calculated as the ratio of power to the compressor and power into the generator excluding the power used for battery charging. In Figure 4.13, battery power supply efficiency is the ratio of power to the compressor and power out of the battery pack, and in Figure 4.14, battery charging efficiency is the ratio of power into the battery pack and power into the generator excluding the power directly used for moving the compressor.
Besides the power and efficiency performance, a few other details may be of interest to engineers. The generator and motor power factors are plotted in Figure 4.15. A 6-kWh battery pack is selected for this simulation. Its stored energy is used to drive the compressor when the truck engine is off. The battery gets charged when external power sources are available. In this study, the source is the generator. However, the source may also be a “shore” grid power. The battery’s SOC and terminal voltage are simulated in Figure 4.16 and Figure 4.17, respectively.
Figure 4.15. IM and PMSM power factor

Figure 4.16. Battery SOC change

Figure 4.17. Terminal voltage of the battery pack
With all the above power system and thermal system components integrated properly, a desired temperature profile is achieved as shown in Figure 4.18. The compressor is able to supply the right amount of cooling air to maintain product temperature within the desired \(-25 \, ^\circ\text{C}\) to \(-30 \, ^\circ\text{C}\) range.

Figure 4.18. Temperature change in the container
4.2 Detailed Model Simulation

A detailed dynamic power system model with exactly the same parameters is constructed in Simulink/SimPowerSystems. The detailed model includes stepping waveforms from the semiconductor devices at each switching action, taking consideration of snubber circuits. It models the electric machines (PMSM, IM) as differential equations that produce transient waveforms. Filters are also included between components, and harmonics analysis can be performed. However, the model’s simulation sampling time is a maximum 5 µs, and it produces only two simulation seconds in three minutes. Figure 4.19 shows a dynamic response of the rotor speed, stator current, and electromagnetic torque of the IM during the compressor start. The system is chosen to start from 5400 s. Note that it takes about 0.5 s for the rotor to ramp up to the desired speed, 1720 RPM. After another half second when a higher 1780 RPM speed is desired, further transient response is observed. Figure 4.20 shows that the dc bus voltage is feedback controlled to be 700 V all the time, and the inverter PWM modulation index is ramped up gradually to the desired value. In addition, details of the high-frequency switching IM stator voltage can be observed.
The detailed model serves as a validation check for the average model. Although it is not feasible for the detailed model to run as long as a few simulation hours like the average model, it is still possible to simulate the system conditions for a few selected points. Figure 4.21 plots 10 efficiency values on the engine power supply efficiency curve (Figure 4.12), and Table 4.1 lists
the detailed data for these 10 points. Notice that the two efficiency curves are within 5% of each other. Generally, the detailed model efficiency is somewhat lower. This is expected because the detailed model includes complete losses from harmonics, snubber circuits, precise switching actions, and refined machine subsystems. However, for this system, the energy flow and efficiency trend over a long time interval is wanted; hence the loss of the details is not a major concern.

![Figure 4.21. Simulated efficiency comparison for average and detailed models](image)

Table 4.1. Simulated power and efficiency data for the detailed model

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Generator RPM</th>
<th>Motor RPM</th>
<th>Torque (Nm)</th>
<th>Input Power (W)</th>
<th>Output Power (W)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>22240</td>
<td>2909</td>
<td>1786</td>
<td>15.31</td>
<td>5132</td>
<td>3099</td>
<td>0.603</td>
</tr>
<tr>
<td>22270</td>
<td>4056</td>
<td>1782</td>
<td>19.56</td>
<td>5818</td>
<td>3891</td>
<td>0.668</td>
</tr>
<tr>
<td>22300</td>
<td>4233</td>
<td>1779</td>
<td>22.76</td>
<td>6604</td>
<td>4479</td>
<td>0.678</td>
</tr>
<tr>
<td>22330</td>
<td>4227</td>
<td>1778</td>
<td>24.11</td>
<td>6936</td>
<td>4797</td>
<td>0.691</td>
</tr>
<tr>
<td>22360</td>
<td>3899</td>
<td>1777</td>
<td>24.62</td>
<td>6890</td>
<td>4818</td>
<td>0.699</td>
</tr>
<tr>
<td>22390</td>
<td>3689</td>
<td>1777</td>
<td>24.78</td>
<td>6918</td>
<td>4849</td>
<td>0.700</td>
</tr>
<tr>
<td>22420</td>
<td>3571</td>
<td>1777</td>
<td>24.82</td>
<td>6932</td>
<td>4858</td>
<td>0.700</td>
</tr>
<tr>
<td>22450</td>
<td>4188</td>
<td>1777</td>
<td>24.83</td>
<td>7048</td>
<td>4860</td>
<td>0.689</td>
</tr>
<tr>
<td>22480</td>
<td>3863</td>
<td>1777</td>
<td>24.82</td>
<td>6934</td>
<td>4855</td>
<td>0.700</td>
</tr>
<tr>
<td>22510</td>
<td>3347</td>
<td>1777</td>
<td>24.8</td>
<td>6970</td>
<td>4850</td>
<td>0.695</td>
</tr>
</tbody>
</table>
5 EXPERIMENTAL VALIDATION

The system outlined by Figure 2.3 with the desired component specifications is difficult to realize physically at the moment. However, it is possible and reasonable to break the system into three parts and test them individually. The first part, the front end, consists of the generator and the ac-dc rectifier. The battery pack is the second part. The last is the variable frequency ac motor drive, including the dc-ac inverter and the motor.
5.1 Front End Testing

The front end test was conducted by a division of Ingersoll Rand, associated with Thermo King, in Prague, Czech Republic [28]. This 17.3 kVA machine was exactly the same as the one modeled in Simulink. It was used previously as the generator for an electric air conditioning unit in a city bus. Different loads were applied for each of various speed/RPM settings, and the corresponding powers and efficiencies were obtained through direct measurement, as shown in Figure 5.1. In the same test, Figure 5.2 shows the power losses and efficiencies versus speed for each load (torque) applied. The simulated power losses and efficiencies are plotted in dashed lines; and solid lines show the actual data. It can be observed that the simulation power loss prediction is within 6% deviation from the actual data over most of the operating range. The simulated and measured efficiencies are within 1% of each other. Figure 5.3 is a comprehensive efficiency map for this PMSM. The many distributed dots on the figure are actual experimental data points.

![Figure 5.1. PMSM efficiency versus power at different speeds](image_url)
Figure 5.2. PMSM power loss and efficiency versus speed at different loads [29]

Figure 5.3. Efficiency map for PMSM [29]
The ac-dc rectifier was also tested in Prague [28]. A 600 V/40 A PWM rectifier was used. It was connected to the generator output, and power data were obtained for different generator RPMs and output powers, as shown in Figure 5.4. Overall the percent efficiency was high, in the upper 90 percentile. This was expected for a PWM rectifier with these ratings. This matched the model simulation.

![Figure 5.4. Rectifier efficiency versus power for different PMSM speeds [29]](image-url)
5.2 Battery Testing

The second part is the battery test. To validate the improved modeling approach, test data for the $R$ and $C$ constants and open circuit voltage in Figure 3.10 were obtained and plotted against the model simulation. The test data are available from the appendix in [25]. Figures 5.5 to 5.10 show the curve-fitted and measured data for discharging $R$ second, $C$ second, $R$ minute, $C$ minute, $R$ hour, and $C$ hour constants, as functions of SOC, as described in Section 3.5. Figure 5.11 shows the simulated and measured battery cell open circuit terminal voltages as functions of SOC. All the fitted/simulated curves demonstrate close relationships with the measured data without showing severe ups and downs that can cause simulation’s instability.

![Figure 5.5. Measured R_sec constant compared to fitted curve](image1)

![Figure 5.6. Measured C_sec constant compared to fitted curve](image2)
Figure 5.7. Measured $R_{\text{min}}$ constant compared to fitted curve

Figure 5.8. Measured $C_{\text{min}}$ constant compared to fitted curve

Figure 5.9. Measured $R_{\text{hour}}$ constant compared to fitted curve

Figure 5.10. Measured $C_{\text{hour}}$ constant compared to fitted curve
Figure 5.11. Measured battery terminal voltage compared to simulated data
5.3 Motor Drive Testing

The last experiment is the variable frequency ac motor drive test. The test was performed in the Power and Energy Systems lab at the University of Illinois. A scaled-down system was employed for validation. The experimental setup is shown in Figure 5.12. A Leeson three-phase 230/460 V 2 HP 4-pole IM [29] was chosen, and a modular dc-ac inverter was constructed by previous graduate students at the university [30]. Figure 5.13 shows the inverter power stage, and Figure 5.14 shows the control and communication interface. 400 V 40 A IGBTs are used in the power stage, and the control box is based on a TI-2812 DSP and commanded by MATLAB/Simulink [30].
Figure 5.15 is a simulated motor drive characteristic plot for the specified three-phase 230/460 V 12 HP 4-pole IM. It shows the IM torque-speed curve at 60 Hz and also along with its efficiency, power, and current curves. Experiments to verify these curves will be run at various frequencies on the modular inverter and the 2 HP IM. The inverter was controlled by the V/f
technique to vary the frequencies and voltages. Figure 5.16 shows sampled points giving the torque-speed curve at 50, 60, and 70 Hz, respectively. Similarly the efficiency and power curves were obtained in Figures 5.17 and 5.18, respectively. Although the measured data matched the simulated curves (scaled down), it is important to note that the nominal efficiency is 84.0% for the 2 HP IM [29], whereas it is 89.2% for the 12 HP IM, the machine used for simulation.

![Simulated machine parameters for the 12 HP IM](image1)

**Figure 5.15. Simulated machine parameters for the 12 HP IM**

![Measured IM torque speed curve at different frequencies](image2)

**Figure 5.16. Measured IM torque speed curve at different frequencies**
The dynamometer acted as the load and was programmed to impose the torque profile from Figure 5.19 to the IM. The torque profile was selected from Figure 4.7 and scaled to 1/6 of the original to fit the 2 HP machine. Similarly, a speed control command, as shown in Figure 5.20, was realized by the inverter through V/f control. The running time was 720 seconds. During this time, output and input power were measured across the entire motor drive, and an efficiency curve was plotted in Figure 5.21. The measured efficiency was on average about 5% lower than the simulated efficiency. This was expected because the IM used for this experiment has an efficiency value about 5% lower. Nevertheless, the measured efficiency trend closely matched the expected efficiency. This demonstrates that the average model is accurate.

Figure 5.17. Measured IM efficiency versus speed at different frequencies

Figure 5.18. Measured IM power versus speed at different frequencies

The dynamometer acted as the load and was programmed to impose the torque profile from Figure 5.19 to the IM. The torque profile was selected from Figure 4.7 and scaled to 1/6 of the original to fit the 2 HP machine. Similarly, a speed control command, as shown in Figure 5.20, was realized by the inverter through V/f control. The running time was 720 seconds. During this time, output and input power were measured across the entire motor drive, and an efficiency curve was plotted in Figure 5.21. The measured efficiency was on average about 5% lower than the simulated efficiency. This was expected because the IM used for this experiment has an efficiency value about 5% lower. Nevertheless, the measured efficiency trend closely matched the expected efficiency. This demonstrates that the average model is accurate.
Figure 5.19. Desired torque demand for the motor drive

Figure 5.20. Desired speed command for the ac motor drive

Figure 5.21. Measured efficiency compared to simulated efficiency for the motor drive
6 DISCUSSION

The detailed model simulation and experimental validation have demonstrated the accuracy of the average model, which will be used to calculate energy and cost-effectiveness for the hybrid power system. These results will be compared to the conventional power system.

Assumptions on truck operating conditions, drive cycles, and battery pack selections are required in order to calculate energy consumption for different power system configurations. The simulated scenario in Chapter 4 is used and extended to 0 s to 36,000 s to represent a whole day, as described in Table 3.1. Simulation results are similar to those in Figures 4.2 to 4.18. A battery pack is pre-charged from the grid before deliveries, and it is charged by the generator during the deliveries. A 6 kWh battery pack is chosen such that it just gets depleted by the end of the day. The battery is then recharged from the grid. Under these assumptions, the MRU energy used throughout the day is drawn from the generator in addition to a one-time fully charged battery pack.

The generator input energy, computed by integrating the generator input power over time, is found to be 95.15 MJ. The National Petroleum Council estimates that the diesel engine of this medium-duty class 6 truck has a 40% efficiency [8]. Therefore, the total daily diesel energy required is approximately 237.87 MJ. Note that the pre-charged battery pack contains 21.6 MJ. Assuming it is charged with a 90% efficient charger, 24.0 MJ is consumed from the grid. On the other hand, the conventional power system requires 83.19 MJ, calculated by integrating the compressor power. If the compressor is directly coupled to a diesel engine, 332.76 MJ diesel fuel is required, assuming that this engine is light-duty with 25% efficiency [8]. Table 6.1 summarizes energy calculations. The table also includes the total cost per day to supply energy in
hybrid and conventional power systems, assuming 135.6 MJ/gal in the diesel fuel [8] at $4.00/gal and $0.10/kWh for electricity [31].

<table>
<thead>
<tr>
<th></th>
<th>Hybrid</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel fuel (gal)</td>
<td>1.75</td>
<td>2.45</td>
</tr>
<tr>
<td>Electricity (kWh)</td>
<td>6.67</td>
<td>0</td>
</tr>
<tr>
<td>Total energy (MJ)</td>
<td>261.87</td>
<td>332.76</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>7.67</td>
<td>9.80</td>
</tr>
</tbody>
</table>

It can be observed that the hybrid power system saves approximately 71 MJ (0.53 gal of diesel or 19.5 kWh of electricity) and $2.13 per day compared to the conventional system. Note that this is based on the assumption that the truck engine is 40% efficient (hybrid case) and the compressor coupled engine is 25% efficient (conventional case). These efficiency numbers may vary depending on the actual engines chosen. In particular, if the compressor-coupled engine is above 31.8% efficient, the hybrid power system is no longer advantageous. The above analysis shows that the hybrid power system for MRUs is only somewhat efficient. As mentioned in Chapter 1, this hybrid system lacks the possibility of regenerative braking, as used in HEV applications. Nevertheless, the hybrid MRUs at least eliminate pollution while the truck idles. This complies with various regulations and is environmentally friendly.

An ac grid plug-in option inserted between the generator and the rectifier (Figure 2.3) may increase energy savings. This option is enabled when the truck is stopped and a “shore” grid power is available. The battery pack size could be reduced because the compressor is powered directly from the grid. Hence less energy is required to charge the battery from the inefficient
engine/generator combination. In addition, grid power is less expensive than diesel fuel. “Shore” power infrastructure availability is one major difficulty to overcome, and depending on this availability, the battery pack can be reduced by half or even eliminated. Suppose that a plug-in facility is available at every stop with no battery required. A simulation and integration of rectifier input power under three-phase 208 V line-line yields 88.2 MJ. 18.77 MJ is required from the generator while the truck makes deliveries, burning 46.92 MJ of diesel. If half of the plug-in facilities are not available, and a 3 kWh battery pack is needed, 56.1 MJ (including 12 MJ for the battery) and 109.1 MJ are required from the grid and diesel fuel, respectively. Table 6.2 summarizes these two plug-in scenarios. Both options give significant energy and cost savings compared to those in Table 6.1. However, there are drawbacks because plug-in facilities are expensive to build and also involve concerns about public policies and/or cost sharing.

Table 6.2. Energy and cost comparison between plug-in and half plug-in systems

<table>
<thead>
<tr>
<th></th>
<th>Plug-in only</th>
<th>50% Plug-in and 50% battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel fuel (gal)</td>
<td>0.35</td>
<td>0.80</td>
</tr>
<tr>
<td>Electricity (kWh)</td>
<td>24.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Total energy (MJ)</td>
<td>135.12</td>
<td>165.2</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>3.85</td>
<td>4.76</td>
</tr>
</tbody>
</table>

Both the hybrid and plug-in enabled power systems appear to outperform the conventional power system, but one should keep in mind that the conventional system has the least initial fixed cost. From a customer’s perspective, saving is one major priority. Although the conventional system is the cheapest on set, its daily cost accumulates and regular maintenance fee is high. Table 6.3 shows the initial estimated costs for different system topologies discussed above, and Table 6.4 compares total costs for each topology over eight years. For the all-plug-in
option, suppose ten customers share costs to build ten charging stations, each customer is responsible for one station. For the hybrid/plug-in option, only five stations are required, and each customer incurs half the construction cost. The truck is expected to operate 6 days a week, or 312 days per year. Every year the diesel engine for the conventional system requires regular oil/filter and air filter changes at an estimated cost of $500, including labor.

Table 6.3. Initial costs for different power system configurations

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Hybrid</th>
<th>Plug-in only</th>
<th>Hybrid/plug-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-duty engine</td>
<td>$800</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Battery pack and converter</td>
<td>$0</td>
<td>$2650</td>
<td>$0</td>
<td>$1500</td>
</tr>
<tr>
<td>PMSM, IM, power electronic converters, wiring</td>
<td>$0</td>
<td>$2950</td>
<td>$2950</td>
<td>$2950</td>
</tr>
<tr>
<td>Charger and charging station</td>
<td>$0</td>
<td>$0</td>
<td>$4200</td>
<td>$2100</td>
</tr>
<tr>
<td>Total</td>
<td>$800</td>
<td>$5600</td>
<td>$7150</td>
<td>$6550</td>
</tr>
</tbody>
</table>

Table 6.4. Total costs of the first eight years for different power system configurations

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Hybrid</th>
<th>Plug-in only</th>
<th>Hybrid/plug-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning</td>
<td>$800</td>
<td>$5600</td>
<td>$7150</td>
<td>$6550</td>
</tr>
<tr>
<td>In one year</td>
<td>$4358</td>
<td>$7993</td>
<td>$8351</td>
<td>$8035</td>
</tr>
<tr>
<td>In two years</td>
<td>$7916</td>
<td>$10386</td>
<td>$9552</td>
<td>$9520</td>
</tr>
<tr>
<td>In three years</td>
<td>$11474</td>
<td>$12779</td>
<td>$10753</td>
<td>$11005</td>
</tr>
<tr>
<td>In four years</td>
<td>$15031</td>
<td>$15172</td>
<td>$11954</td>
<td>$12490</td>
</tr>
<tr>
<td>In five years</td>
<td>$18590</td>
<td>$17565</td>
<td>$13155</td>
<td>$13975</td>
</tr>
<tr>
<td>In six years</td>
<td>$22148</td>
<td>$19958</td>
<td>$14356</td>
<td>$15460</td>
</tr>
<tr>
<td>In seven years</td>
<td>$25706</td>
<td>$22351</td>
<td>$15557</td>
<td>$16945</td>
</tr>
<tr>
<td>In eight years</td>
<td>$29264</td>
<td>$24744</td>
<td>$16758</td>
<td>$18430</td>
</tr>
</tbody>
</table>
Figure 6.1 plots the data in Table 6.4. The figure shows that after three years the options with plug-in outperform the conventional system, and after four years, the hybrid option also becomes advantageous. Note that a large portion of plug-in fixed costs comes from chargers or charging stations. It may take less time for break-even if such cost is not directly out of a customer’s pocket or if a “charging station” is just an electric outlet. The purely plug-in system is somewhat but not much cheaper than the hybrid/plug-in option in the long run. However, the hybrid/plug-in configuration is more adaptive and can function if a charging station is not available at every stop.

![Figure 6.1. Comparison of total costs over eight years for different topologies](image)

The analysis above is based on the operating conditions described in Chapter 4. Other operating conditions may likely yield different energy and cost savings results. For example, if the truck makes mostly inter-city deliveries, the plug-in options are less attractive because there are few stops. In this case, the hybrid power system seems the best option to comply with environmental regulations. With other scenarios considered, a comprehensive energy and cost savings analysis is required for the future in order to target different customers’ MRU applications.
7 CONCLUSION AND FUTURE WORK

A hybrid power system for mobile refrigeration applications has been designed, modeled, and tested. The proposed average model, interfaced with the thermal system model, has been validated by comprehensive simulation and experimental work. The average model with improved battery formulation enhances accuracy and robustness for the battery subsystem simulation. In addition to fast simulation, the model is flexible and can run at desired times, power levels, and drive cycles. A user-friendly model block library, including various machine types (IM, PMSM, etc.), battery types (Li-ion, lead-acid, etc.), along with different power converters, has been released. These model blocks can be substituted in the system on a modular basis for various potential prototypes. The average model has been applied as part of a complete thermal-electric system simulation and serves as a basis for future energy storage selection and hybrid system optimization studies.

There are a few comments about the average model’s limitations and considerations. 1) The model runs fast by trading off fidelity. The model is not intended for use in detailed hardware design, and it is not helpful for observing system behavior in a short time interval especially during traction system’s instantaneous acceleration or deceleration. 2) Various drive cycles and loading profiles are appropriate for a most thorough system analysis. The scenario described in this thesis is keeping produce frozen inside the truck container on a hot summer day for a local delivery truck. Another scenario of a truck’s non-stop running on a highway for a few hours will have a different output result. It may also be required to maintain a certain produce temperature above 0 °C on a -20 °C winter day. In this case, the MRU must supply warm air, and depending on the heating unit, the power system may or may not be modified. 3) The hybrid model presented is based on a parallel-hybrid topology. On the other hand, a series-hybrid or
other topology may be equivalently functional. One alternative directly couples the PMSM with the IM. The idea is feasible because the PMSM itself acts like a volts-per-hertz control due to the linear relationships between $V$, $f$ and rotor speed. However, further study may be required, as the PMSM has a wide range of outputs and there are limitations. 4) The system was validated through three parts in Chapter 5. A complete test at full scale needs to be performed to completely demonstrate the model accuracy.

The electrification of an MRU is a recent topic in industry and has enormous opportunities for research and development. The average model presented in this thesis may lead to multiple directions of improvement. 1) Advanced existing or novel control techniques can be applied to the motor drive for highly efficient and precise internal loading requirement. This may be particularly beneficial for highly temperature-sensitive products such as medications. 2) A multilevel converter based motor drive is worth investigating for improving efficiency and reducing motor stress, especially under high power requirements. The system can be equipped with different battery types such as nickel-metal hydride or alternative energy storage devices such as fuel cells. These energy devices can be studied for performance, cost-effectiveness, and efficiency. 3) A grid plug-in is definitely an option, as discussed in Chapter 6. The typical power requirement is less than 5 kW, and a three-phase shore power is readily available. A comprehensive energy and cost analysis for different system configurations and truck operating situations can be further pursued. 4) We want to know what is the optimal operation strategy considering the truck engine, battery, and plug-in on and off status, to have the highest efficiency while enjoying a low cost. 5) Try to explore another modeling strategy, such as the piece-wise linear method suggested by [19], which is capable of reaching the simulation speed goal but also providing more details.
REFERENCES


APPENDIX A SIMULINK MODELS

A.1 High-Level Integrated Thermo-Electric Model

Figure A.1 High-level integrated thermo-electric model in MATLAB/Simulink

A.2 Average Model for Hybrid Power Systems

Figure A.2 High-level hybrid power systems average model in MATLAB/Simulink
A.3 Detailed Model for Hybrid Power Systems

Figure A.3 High-level hybrid power systems detailed model in MATLAB/Simulink
APPENDIX B MATLAB PROGRAMS

B.1 IM Parameters Calculation MATLAB Code

close all, clear all, clc

% Two rated voltages (this is line-line RMS)
V_rated = [460; 400]; % first entry is bigger than the second entry

% Corresponding frequencies in Hz
Freq_rated = [60; 50];

% Corresponding locked currents
I_locked = [123; 116];

% Locked rotor torque at first frequency
T_locked = 126;

% Number of poles
pole = 4;

% Power factor at first frequency
PF = 0.88;

% Efficiency at first frequency
Eff = 0.892;

% Rated horse power at first frequency
HP = 12;

% Rated RPM at first frequency
RatedRPM = 1750;

% End of inputs
%-------------------------------------------------------------

Z_rated = (V_rated/sqrt(3))./I_locked; % per phase
% Z_rated = (R1+R2) + j*2*pi*freq*(L1+L2) = R + j*2*pi*freq*L

L = sqrt(((Z_rated(1))^2-(Z_rated(2))^2)/((2*pi*Freq_rated(1))^2-(2*pi*Freq_rated(2))^2));
% R^2 + (2*pi*f*L)^2 = Z^2, freq is different
R = sqrt(((Z_rated(1))^2-(Z_rated(2))^2)/((2*pi*Freq_rated(1))^2-(2*pi*Freq_rated(2))^2));

L2 = 0.5*L
L1 = 0.5*L
% Usually L1=L2=0.5L

R2 = T_locked*(2*pi*Freq_rated(1)/(pole/2))/3/(I_locked(1))^2
% T = 3*I^2*R2 / (2*pi*f/pole_pairs)
R1 = R - R2
\[ I_{1\_\text{mag}} = \frac{\text{HP} \cdot 746}{\text{Eff} \cdot \text{PF} \cdot 3 \cdot \sqrt{3}}; \quad \text{1 HP = 746 W} \]

\[ \text{Angle1} = -1 \cdot \cos(\text{PF}); \quad \% \text{Lagging power factor for IM} \]

\[ I_1 = I_{1\_\text{mag}} \cdot \exp(j \cdot \text{Angle1}); \quad \% \text{Phasor format} \]

\[ V_{\text{shunt}} = \frac{V_{\text{rated}(1)}}{\sqrt{3}} - I_1 \cdot (R_1 + j \cdot 2 \cdot \pi \cdot \text{Freq\_rated}(1) \cdot L_1); \]

\[ V_{\text{shunt}} = V_{\text{in}} - I_1 \cdot Z_1; \quad \text{Vin as reference with angle 0} \]

\[ \text{SyncRPM} = \frac{120 \cdot \text{Freq\_rated}(1)}{\text{pole}}; \]

\[ \% \text{SyncRPM = 120*}\text{f/pole} \]

\[ \text{slip} = 1 - \frac{\text{RatedRPM}}{\text{SyncRPM}}; \]

\[ I_2 = \frac{V_{\text{shunt}}}{R_2 / \text{slip} + j \cdot 2 \cdot \pi \cdot \text{Freq\_rated}(1) \cdot L_2}; \]

\[ I_2 = \frac{V_{\text{shunt}}}{Z_2}; \]

\[ I_{\text{shunt}} = I_1 - I_2; \]

\[ Y_{\text{shunt}} = \frac{I_{\text{shunt}}}{V_{\text{shunt}}}; \quad \% \text{Admittance of shunt branch} \]

\[ Y_{\text{shunt}} = \frac{1}{R_c} + \frac{1}{j \cdot 2 \cdot \pi \cdot f \cdot L_m} \]

\[ L_m = \frac{1}{\text{abs}(\text{imag}(Y_{\text{shunt}})) / (2 \cdot \pi \cdot \text{Freq\_rated}(1))}; \]

\[ R_c = \frac{1}{\text{abs}(\text{real}(Y_{\text{shunt}}))}; \]

\[ \% \text{Match the corresponding component of Y}_{\text{shunt}} \]

### B.2 PMSM Parameters Calculation MATLAB Code

```matlab
clear all, close all, clc

\% RPM column:
\text{RPM} = [1500; 1875; 2250; 3000; 4500; 5000];

\% No load voltage at 20C (this is line-line RMS)
\text{Volt} = [195; 244; 293; 390; 585; 650];

\% Frequency column
\text{Freq} = [100; 125; 150; 200; 300; 334];

\% End of inputs
\%
\% -----------------------------------------------

\text{Frequency\_Constant} = \text{mean}(\text{Freq}/\text{RPM}) \cdot 1000 \% \text{linear relations}
\text{Voltage\_Constant} = \text{mean}(\text{Volt}/\text{RPM}) \cdot 1000/\sqrt{3} \% \text{linear relations and convert to line-neutral RMS}
```