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New Load Demand for Electric Vehicles and Its Harmonic Impacts on Power System Distribution Transformers

Maryam Kazerooni

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New Load Demand for Electric Vehicles and Its Harmonic Impacts on Power System Distribution Transformers

by

Maryam Kazerooni

A Thesis
Submitted to the Faculty of Graduate Studies through Electrical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2012

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New Load Demand for Electric Vehicles and Its Impacts on Power System Distribution Transformers

by

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## Declaration of Previous Publication

This thesis includes four original papers that have been previously submitted for publication in peer reviewed journals, as follows:

<table>
<thead>
<tr>
<th>Thesis Chapter</th>
<th>Publication title/full citation</th>
<th>Publication status</th>
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<tr>
<td>Chapter 4</td>
<td>M. Kazerooni, and N. C. Kar, “Optimal Load Management of EV Battery Charging and Optimization of Harmonic Impacts on Distribution Transformers,” to appear in <em>Proceedings of IEEE Canadian Conf. on Electrical and Computer Eng.</em>, April/May 2012.</td>
<td>accepted for publication</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>M. Kazerooni, S. Hamidifar, and N. C. Kar, &quot;Analytical Modelling and Parametric Sensitivity Analysis for the PMSM Steady-State Performance Prediction,&quot; accepted for publication subject to minor revision to the <em>IET Electric Power Applications</em>.</td>
<td>submitted</td>
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The growing concern about CO₂ emissions and dependency on foreign oil contributes to the increasing application of electric vehicles (EVs). EV battery chargers are non-linear loads and large-scale application of EVs increases the grid harmonics significantly. The grid harmonics have negative impacts on the components of the power system including distribution transformers. In this thesis, the potentials for EVs to penetrate the transportation market are studied and the additional load demand when EV penetration achieves its full potential is estimated. Loss and thermal modeling of distribution transformers incorporating EV penetration are presented and the impacts of additional EV load demand on load loss, temperature and aging acceleration factor of a sample 100 kVA distribution transformer is estimated. The ability of the existing power system to accommodate the additional EV load demand without threatening the safe operation of distribution transformers (DTs) is evaluated based on the calculation results.

To increase the capacity of the existing power system in accommodating the new EV load demand, an optimal charging schedule based on optimization of negative impacts on DTs is proposed. In this regard, EV charging load is formulated as an optimization problem and Newton Method and Karush-Kuhn-Tucker (KKT) optimality conditions are investigated as effective optimization algorithms for solving the developed optimization problem. Using the proposed charging schedule, the impacts of EV penetration on a sam-
ple 100 kW distribution transformer is studied and the effectiveness of the proposed charging schedule is validated through a comparative study.

Moreover, this thesis investigates application of permanent magnet synchronous motors (PMSMs) in EVs as a second approach for reducing the negative impacts of EV charging on DTs. Controlling PMSMs based on their efficiency maps contributes to increasing the efficiency of EV powertrain and consequently reducing the EV load demand. Considering the significance of accurate modeling in the control of PMSM, this thesis focuses on accurate modeling of PMSM and the sources of error in PMSM steady-state performance estimation.

Inaccuracy in the PMSM steady-state performance calculation corresponds to the parameter error and model imprecision. Accurate determination of the PMSM parameters may encounter various complications due to its rotor structure and drive design. Therefore, the PMSM performance calculation is generally vulnerable to inaccuracy because of the parameter error. This thesis studies the effect of parameter error on the inaccuracy of the performance calculations. Several methods for determining the PMSM armature resistance, flux linkage constant and d- and q-axis inductances with varying level of accuracy are proposed. The presented methods are applied to a laboratory PMSM and the sensitivity of the PMSM output power to the equivalent circuit parameters is analyzed based on the experimental results. In addition, this thesis contributes to accurate performance estimations of the PMSM by developing a precise model that incorporates the saturation saliency and core losses. The accuracy of the proposed model is compared with the conventional dq-axis model and its higher accuracy is validated through experimental results.
Acknowledgments

I would like to thank my mother and father for their supports during the writing of this thesis, and Dr. Narayan C. Kar for his supervision during my Master study.
# Table of Contents

Declaration of Previous Publication ........................................................................ III

Abstract ...................................................................................................................... V

Acknowledgments ...................................................................................................... VII

List of Figures ........................................................................................................... X

List of Tables ............................................................................................................ XII

Nomenclature .......................................................................................................... XIII

1 INTRODUCTION .................................................................................................... 1

   1.1 Overview ......................................................................................................... 1
   1.2 EV Load Management ..................................................................................... 2
   1.3 Efficiency of EV Powertrain ........................................................................... 3
   1.4 Investigations .................................................................................................. 4
   1.5 Novelties and Contributions .......................................................................... 5
   1.6 Structure of the Thesis .................................................................................... 6

2 LITERATURE REVIEW .......................................................................................... 7

   2.1 EV Market and Its impacts on Power System ............................................... 7
   2.2 Coordination of EV Charging .......................................................................... 8
   2.3 Application of PMSM in EVs ......................................................................... 9
   2.4 Accurate Modeling of PMSM ................................................................------- 10
   2.5 PMSM Parameter Determination .................................................................... 11

3 IMPACTS OF EV CHARGING ON TRANSFORMERS ........................................ 13
3.1 Load Demand for EVs ................................................................. 14
3.2 Modeling of Transformers .......................................................... 17
  3.2.1 Loss Model ........................................................................... 17
  3.2.2 Thermal Model ....................................................................... 18
  3.2.3 Maximum Permissible Current ............................................. 19
3.3 Incorporating EV penetration in Transformer Model ................. 19
3.4 Calculations and Experimental Results ...................................... 20

4 **OPTIMIZATION OF CHARGING SCHEDULE** .................................................. 29

  4.1 **THE OPTIMIZATION PROBLEM** .................................................. 29
  4.2 **KARUSH-KUHN-TUCKER CONDITIONS** ....................................... 31
  4.3 **NEWTON METHOD** .................................................................. 33
  4.4 **CALCULATED RESULTS** .............................................................. 34
  4.5 **SMART EV CHARGING** ............................................................... 41

5 **PMSM STEADY-STATE MODELING** ......................................................... 44

  5.1 Parameter Determination ............................................................... 46
    5.1.1 Calculation of Parameters ...................................................... 46
    5.1.2 Measurement of Parameters ............................................... 47
  5.2 Calculated and Experimental Results............................................. 52
  5.3 Analytical Evaluation of the Presented Methods ......................... 58
  5.4 Parametric Sensitivity Analysis ..................................................... 60
  5.5 Novel d-q Axis Model of the PMSM ............................................. 64
    5.5.1 Estimation of Core Loss Resistance ....................................... 67
    5.5.2 Verification of the Model Accuracy through Experimentation .... 68

6 **CONCLUSIONS AND FUTURE WORKS** .................................................. 71

  6.1 Conclusions .................................................................................. 71
  6.2 Future Works ................................................................................ 73

**Bibliography** .................................................................................... 75

**Vita Auctoris** ................................................................................... 82
List of Figures

Fig. 3.1. Charging profile of the EV batteries................................................................. 15
Fig. 3.2. The charging profile and load demand of EV batteries................................. 16
Fig. 3.3. The experimental set-up to measure harmonics of charging current............... 21
Fig. 3.4. The measured current and voltage of the battery charger............................. 22
Fig. 3.5. Harmonic spectrum of the charging current.................................................. 22
Fig. 3.6. Harmonic spectrum of the grid current.......................................................... 23
Fig. 3.7. Approximated USA daily load profile in 2011............................................... 23
Fig. 3.8. Effect of additional charging load on losses.................................................... 25
Fig. 3.9. Effect of additional charging load on the temperature.................................... 26
Fig. 3.10. Effect of additional charging load on aging acceleration factor..................... 26
Fig. 3.11. Average of the load loss components........................................................... 27
Fig. 3.12. Average of the transformer temperature....................................................... 27
Fig. 3.13. Average and maximum of aging acceleration factor .................................... 28
Fig. 4.1. Diagrammatic representation of Newton method........................................... 35
Fig. 4.2. Optimal charging profile for EVs................................................................. 36
Fig. 4.3. Calculated load loss for smart EV charging.................................................... 36
Fig. 4.4. Calculated hottest-spot temperature for smart EV charging.......................... 37
Fig. 4.5. Calculated aging acceleration factor for smart EV charging.......................... 38
Fig. 4.6. Optimal load demand at different EV penetrations........................................ 38
Fig. 4.7. The average of load loss components............................................................ 39
Fig. 4.8. The average of transformer temperatures ................................................................. 40
Fig. 4.9. The average and maximum of aging acceleration factor ........................................... 41
Fig. 5.1. The PMSM efficiency map .......................................................................................... 45
Fig. 5.2. Circuit connection for measurement of d- and q-axis inductances ............................. 49
Fig. 5.3. Circuit connection for DC standstill test ................................................................. 50
Fig. 5.4. Phasor diagram of for measurement of q-axes inductance ......................................... 52
Fig. 5.5. Back EMF and its harmonic distortions ..................................................................... 52
Fig. 5.6. Experimental setup for DC standstill test ............................................................... 54
Fig. 5.7. Transient current response in a DC standstill test .................................................... 54
Fig. 5.8. Transient response to a step DC voltage for q-axis measurement ......................... 55
Fig. 5.9. d- and q-axis inductances obtained from magnetic flux measurement .................... 56
Fig. 5.10. q-axis inductance obtained on-load test .............................................................. 57
Fig. 5.11. Performance calculation employing methods of d- and q-axis inductances
determination .......................................................................................................................... 61
Fig. 5.12. Performance calculation employing methods of flux linkage constant
determination .......................................................................................................................... 62
Fig. 5.13. Performance calculation employing methods of armature resistance
determination .......................................................................................................................... 62
Fig. 5.14. Modeling of the under excited PMSM incorporating core losses ......................... 65
Fig. 5.15. Novel d-q-axis model incorporating core losses ..................................................... 66
Fig. 5.16. Calculating the out power using the proposed model ............................................. 69
List of Tables

TABLE I. Ratings and Specifications of the Sample Distribution Transformer ............ 20
TABLE II. PMSM Used in the Investigations .................................................................. 53
TABLE III. PMSM Parameters Obtained from Presented Methods.............................. 57
TABLE IV. Sensitivity Analysis of the Output Power .................................................... 63
TABLE V. Estimated Core Loss Resistance at Various Speeds..................................... 68
TABLE VI. Root Mean Square Error of the Output Power at Different Speeds ............ 70
TABLE VII. Root Mean Square Error of the Output Power at Different Current......... 70
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{LL}$</td>
<td>load loss</td>
</tr>
<tr>
<td>$P_{EC}$</td>
<td>winding eddy-current loss</td>
</tr>
<tr>
<td>$P_{OSL}$</td>
<td>other stray loss</td>
</tr>
<tr>
<td>$P_{cu}$</td>
<td>copper loss</td>
</tr>
<tr>
<td>$P_{LL-R(pu)}$</td>
<td>per unit load loss at rated conditions</td>
</tr>
<tr>
<td>$P_{OSL-R(pu)}$</td>
<td>per unit other stray loss at rated conditions</td>
</tr>
<tr>
<td>$P_{EC-R(pu)}$</td>
<td>per unit winding eddy-current loss at rated conditions</td>
</tr>
<tr>
<td>$P_{cu-R(pu)}$</td>
<td>per unit copper loss under rated conditions</td>
</tr>
<tr>
<td>$I_{(pu)}$</td>
<td>per unit rms load current</td>
</tr>
<tr>
<td>$h$</td>
<td>harmonic order</td>
</tr>
<tr>
<td>$h_{max}$</td>
<td>highest significant harmonic number</td>
</tr>
<tr>
<td>$I_h$</td>
<td>ratio of $h^{th}$ harmonic to fundamental</td>
</tr>
<tr>
<td>$I_1$</td>
<td>rms fundamental of load current</td>
</tr>
<tr>
<td>$F_{HL}$</td>
<td>harmonic loss factor for winding eddy currents</td>
</tr>
<tr>
<td>$F_{HL-STR}$</td>
<td>harmonic loss factor for other stray losses</td>
</tr>
<tr>
<td>$I_{(pu)}$</td>
<td>per unit rms load current</td>
</tr>
<tr>
<td>$\theta_{TO}$</td>
<td>top-oil-rise over ambient temperature</td>
</tr>
<tr>
<td>$\theta_{TO-R}$</td>
<td>rated top-oil-rise over ambient temperature</td>
</tr>
<tr>
<td>$P_{NL}$</td>
<td>no load loss</td>
</tr>
<tr>
<td>$\theta_g$</td>
<td>hottest-spot conductor rise over top-oil temperature</td>
</tr>
<tr>
<td>$\theta_{g-R}$</td>
<td>rated hottest-spot conductor rise over top-oil temperature</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>winding-rise over ambient temperature</td>
</tr>
<tr>
<td>$\theta_A$</td>
<td>ambient temperature</td>
</tr>
<tr>
<td>$\theta_H$</td>
<td>transformer hottest spot temperature</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>FAA</td>
<td>aging acceleration factor</td>
</tr>
<tr>
<td>$P_{EV}$</td>
<td>EV penetration</td>
</tr>
<tr>
<td>$I_{n,ev}$</td>
<td>ratio of $n^{th}$ harmonic to fundamental for charging current</td>
</tr>
<tr>
<td>$I_n$</td>
<td>ratio of $n^{th}$ harmonic to fundamental for grid current</td>
</tr>
<tr>
<td>N</td>
<td>set of natural numbers</td>
</tr>
<tr>
<td>H</td>
<td>set of natural numbers which are equal or smaller than 24</td>
</tr>
<tr>
<td>$\rho^h$</td>
<td>hourly EV penetration</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>daily EV penetration vector</td>
</tr>
<tr>
<td>$f$</td>
<td>objective function of the optimization problem</td>
</tr>
<tr>
<td>L</td>
<td>Lagrangian associated with the primal problem</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Lagrangian multiplier associated with the equality constraint</td>
</tr>
<tr>
<td>$A, B$</td>
<td>Lagrangian multiplier vectors associated with lower and upper bound constraint</td>
</tr>
<tr>
<td>$\alpha^h$</td>
<td>$h^{th}$ Lagrangian multiplier associated with the lower bound constraint</td>
</tr>
<tr>
<td>$\beta^h$</td>
<td>$h^{th}$ Lagrangian multiplier associated with the upper bound constraint</td>
</tr>
<tr>
<td>k</td>
<td>Lagrange dual function of the primal function</td>
</tr>
<tr>
<td>$\lambda_N$</td>
<td>Newton decrement</td>
</tr>
<tr>
<td>$\nu_N$</td>
<td>Newton search direction</td>
</tr>
<tr>
<td>$\omega_N$</td>
<td>Newton step size</td>
</tr>
<tr>
<td>$R_a, L_i$</td>
<td>armature resistance and leakage inductance</td>
</tr>
<tr>
<td>$N, p$</td>
<td>number of turns per phase and number of pole pairs</td>
</tr>
<tr>
<td>$L_s$</td>
<td>armature stack effective length</td>
</tr>
<tr>
<td>$h_M$</td>
<td>height of the permanent magnets</td>
</tr>
<tr>
<td>$g, g_q$</td>
<td>air-gap length in d- and q- axis</td>
</tr>
<tr>
<td>$\tau$</td>
<td>pole pitch</td>
</tr>
<tr>
<td>a</td>
<td>number of parallel paths</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>electric conductivity</td>
</tr>
<tr>
<td>$s_a$</td>
<td>conductor cross sectional area</td>
</tr>
<tr>
<td>$\lambda_{f}, E_f$</td>
<td>flux linkage constant and excitation voltage</td>
</tr>
<tr>
<td>$k_w$</td>
<td>stator winding coefficient</td>
</tr>
<tr>
<td>$B_r$</td>
<td>remnant magnet flux density</td>
</tr>
<tr>
<td>$\mu_{rec}$</td>
<td>relative recoil permeability</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>magnetic permeability of free space</td>
</tr>
<tr>
<td>$L_{ds}, L_{dq}$</td>
<td>d- and q-axis synchronous inductances</td>
</tr>
<tr>
<td>$\lambda_{sl}$</td>
<td>per-slot leakage permeance</td>
</tr>
<tr>
<td>s</td>
<td>number of stator slots</td>
</tr>
<tr>
<td>$V_{DC-150%}$</td>
<td>DC voltage corresponding to 150% of the rated current</td>
</tr>
<tr>
<td>$V_{DC-100%}$</td>
<td>DC voltage corresponding to rated current</td>
</tr>
</tbody>
</table>
I_{DC-150\%}  DC current corresponding to 150% of the rated current
I_{DC-100\%}  DC current corresponding to rated current
t(t), v(t)  armature instantaneous current and voltage
t  time
I_{DC}  PMSM steady-state DC current
R_{CKT}  circuit resistance in the DC standstill test
\tau_d, \tau_q  time constants for d- and q-axis inductance measurements
I_a, V_a  phase ‘a’ current and voltage
L_{aa}  phase ‘a’ self-inductance
M_{ac}  mutual inductance between ‘a’ and ‘c’ phases
\omega_s, \omega_r  angular frequency of rotor and stator
V_s, I_t  stator terminal voltage and current
a_0, a_1  coefficients of L_{aa} fitted curve
b_0, b_1  coefficients of M_{ac} fitted curve
\theta, \delta  phase and torque angle
S_\rho  sensitivity of \gamma to \rho
\gamma_{ex}, \gamma_{cal}  experimental and calculated performance factor
\rho_{act}, \rho_{det}  actual value and determined value of the parameter
E_{id}, E_{iq}  d- and q-axis internal voltage
R_c, R_{ce}, R_{ch}  core, eddy-current and hysteresis loss resistances
L_{md}, L_{mq}  d- and q-axis magnetizing inductances
I_d, I_q  d- and q-axis currents
V_d, V_q  d- and q-axis voltages
\bar{L}_{md}, \bar{L}_{mq}  d- and q-axis inductances including the core loss
\varepsilon  q-axis excitation voltage coefficient
\alpha  q-axis inductance to core loss resistance ratio
\bar{R}_a  armature resistance incorporating the core loss effect
k_d, k_q  excitation voltage coefficients for d- and q-axis currents
E_{id}, E_{iq}  d- and q-axis excitation voltages including core losses
a_d, a_q  Fourier series coefficients of d- and q-axis inductances
f_d, f_q  d- and q-axis Fourier series frequencies
N_f  number of the terms in the Fourier series
P_{rot}, P_{cu}  mechanical losses, and copper losses
P_{in}, P_{out}, P_s  input power, output power, and semi-output power
1 INTRODUCTION

1.1 Overview

The growing concern about CO$_2$ emissions and dependency on foreign oil contributes significantly to the increasing application of electrified vehicles (EVs) including all-electric vehicles and plug-in hybrid electric vehicles. New developments in batteries and battery chargers are gradually resolving the short operation range and long battery charging time of EVs. According to [1], the EV market has the potential to comprise more than 25% of the entire car and light-duty truck market by 2020. Accordingly, the load demand of EV battery chargers is expected to constitute a remarkable percentage of the total load demand in future.

EV battery chargers are non-linear loads and large-scale application of EVs increases the grid harmonics significantly. Currently, the load demand of EV battery chargers is a small fraction of the total load demand. Therefore, the harmonic effects of battery chargers are compensated by other linear loads of the distribution system. In future, significant percentage of the total load demand will be allocated to EV battery charging. Consequently, the harmonic impacts of the battery chargers on the power quality of distribution system will be remarkable.
Grid harmonics have negative impacts on the components of the power system. One of the major components of the power system is distribution transformer. Distribution transformers are used in distribution centers for stepping down the grid voltage to the users’ desired voltage. Transformers are mostly designed for feeding linear loads at rated frequency. The current harmonics produced by EV battery chargers create additional loss in transformers. Consequently, the transformer temperature increases and its lifetime declines significantly. Distribution transformers have high costs of initial installation. In addition, replacing them at the end of their lifetime without any grid disconnection has great financial and technical difficulties. Therefore, sufficient preparations are required to accommodate the new load demand for EV charging without threatening the life time of distribution transformers.

1.2 EV Load Management

Load management of EV charging is an effective approach for optimizing the grid harmonics and their impacts on DTs. The load management programs including the real-time pricing, day-ahead pricing, and time-of-use pricing contribute to power system reliability and utility economics [2]. Real-time pricing (RTP) offers a time-varying pricing that maximizes the utility benefits and system reliability. In conventional load management programs, the costs of producing electricity at different times of the day, the load balance, and the customer outage costs are the main factors in designing the pricing schemes. However, to accommodate the new EV load demand, grid harmonics and their impacts on distribution transformers should be considered in the design of load management programs as well.

EV users are motivated by financial incentives to participate in RTP programs. However, they may not respond effectively to RTP due to lack of knowledge about how to schedule their EV charging based on electricity price. Moreover, it is difficult and time consuming for the users to constantly monitor the hourly prices. In this regard, smart automation systems are utilized for controlling the energy consumption of the battery chargers and optimizing the benefits of the RTP. Smart systems enable the EV users to respond effectively to RTP by minimizing their electricity payment and disruption.
1.3 Efficiency of EV Powertrain

Another suitable solution for reducing the negative impacts of EV charging on transformers is to decrease the total load demand for EV charging. Increasing the efficiency of the EV powertrain results in reduction in energy consumption ratio and consequently the EV daily load demand. One of the major components of the EV powertrain is the Electrical motor. Various types of motors with varying efficiencies are used in commercial electric vehicles. Nissan LEAF is a leading technology in hybrid electric vehicles which its electric motor is a 80 kW, 280 Nm synchronous motor. In Tesla Roadster, a 212 kW induction motor is investigated. Mitsubishi has designed a new electric vehicle called i MiEV and used a 47kW permanent magnet synchronous motor in this vehicle.

Application of induction motor in EVs simplifies the control drive system and increases the stability of the powertrain. However, the efficiency of induction motor is comparatively lower due to stray losses in the rotor. Therefore, application of synchronous motor and PMSM in EVs is preferable when higher efficiency is required. These two types of motor have high power density because of the additional DC excitation in the rotor. Besides, the rotor saliency in SM and PMSM produces an additional reluctance torque which contributes to their high power density. When the EV electric motor has higher power density, for a certain power rating, its size and weight is smaller. Consequently, the energy consumption ratio and the daily load demand of the vehicle are smaller. Comparing with SM, PMSM has higher efficiency due to elimination of DC windings in the rotor. Application of PMSM in EVs increases the efficiency of the powertrain significantly and simplifies the motor maintenance and also Cooling.

The efficiency of PMSM at different operating conditions is determined by its efficiency map. Therefore, controlling the PMSM based on the efficiency map increases the efficiency of EV powertrain. In order to design an effective controller, accurate modeling of PMSM is required. Parameters’ inaccuracy and model inaccuracy are the two sources of error in PMSM modeling. Sensitivity of PMSM modeling to these two sources of error determines the level of accuracy which is required for PMSM model and parameters.
1.4 Investigations

Considering the growing application of EVs, it is essential to study the negative impacts of EV charging on lifetime of DTs. Estimating the additional load demand for EVs and its consequent effects on DTs determines the ability of the existing power system to accommodate the new load demand for EVs. Managing EV load demand along with increasing EVs’ efficiency can be investigated for governing the safe operation of distribution transformers.

In this thesis, the potentials for EVs to penetrate the transportation market are studied and the additional load required for charging EVs is estimated. Moreover, loss and thermal modeling of transformers including the harmonics are thoroughly discussed. A sample 100 kVA distribution transformer is investigated for studying the impacts of EV penetration on DTs and the ability of the existing power system to accommodate the new EV load demand is evaluated based on calculation results.

To minimize the harmonic impacts on DTs, EV charging load is formulated as an optimization problem. The developed optimization problem is solved using Newton Method and a novel EV load management program is proposed. The proposed program offers an optimal charging schedule which minimizes the harmonic impacts of EV charging on DTs.

The effectiveness of the proposed charging schedule is validated through a comparative study. In this regard, the harmonic impacts of EV penetration on a sample 100 kW distribution transformer for both smart EV charging and uncontrolled off-peak charging are investigated and the effectiveness of the novel load management program is demonstrated through calculation results.

The proposed charging schedule can be implemented by designing an optimal pricing scheme in real-time pricing (RTP). Therefore, the EV users are encouraged by financial incentives to charge their vehicles in accordance with the optimal charging schedule. In order to optimize the benefits of the RTP, smart automation systems for EV battery chargers are utilized. In this thesis, a smart system for EV chargers is designed based on optimization of users’ electricity payment and disruption. In this regard, a mathematical model for energy consumption of the battery chargers is developed. Optimizing the bene-
fits of the EV users is achieved by formulating the energy consumption model as an optimization problem.

Moreover, this thesis investigates application of PMSM in EVs as an effective approach for reducing the EV load demand. Accurate modeling of PMSM contributes to designing an effective controller which maximizes PMSM efficiency. In this thesis, accurate modeling of PMSM at steady-state conditions is thoroughly investigated. Several methods for parameters determination with varying level of accuracy are presented and the sensitivity of PMSM modeling to parameter error is studied through experimentation. Moreover, an accurate d- and q-axis model of PMSM including the saturation saliency and core losses is developed. The accuracy of the proposed model is compared with the conventional d- and q-axis model and its higher accuracy is validated through experimental results.

1.5 Novelties and Contributions

In this thesis, the potentials for EVs to penetrate the transportation market are studied and the additional load demand when EV penetration achieves its full potential is estimated. Moreover, novel loss and thermal models of distribution transformers incorporating EV penetration is presented. To minimize the negative impacts of EV charging on DTs, a new EV load management program is proposed. The proposed EV load management program can be implemented in RTP environment by using smart systems for EV chargers. In this regard, a new design for smart systems is proposed which is suitable for EV battery chargers.

Regarding application of PMSM in EVs, new methods for determining PMSM d- and q-axis inductances are proposed. Besides, experimentation is investigated as a novel approach for performing parametric sensitivity analysis of PMSM. Finally, for accurate modeling of PMSM, a novel d- and q-axis model including core losses and saturation is developed.
1.6 Structure of the Thesis

This thesis is organized as follows: chapter 2 reviews current knowledge and contributions to electric vehicles and the impacts of their charging on distribution transformers. In chapter 3, the additional load demand required for charging EVs at 25% EV penetration is estimated and its negative impacts on distribution transformers is studied. Optimization of EVs’ charging schedule is presented in chapter 4 and a novel load management program is proposed. Chapter 5 investigates application of PMSM in EVs and presents accurate modeling of PMSM at steady-state conditions. Conclusions are given in the final section. Conclusions and future works are presented in the final chapter.
Chapter 2

2 LITERATURE REVIEW

This chapter reviews the relevant literature in EV market, its impacts on power system infrastructures and also previous investigations on reducing the negative impacts of EVs on power system.

2.1 EV Market and Its impacts on Power System

To prepare the power system for accommodating the future EV load demand, it is essential to investigate the EV market and its potentials to penetrate the transportation market [3]. For estimating EV penetration in future, EV battery technologies, driving patterns, EV energy management and also vehicle to grid technology are studied. According to [1], EVs have the potential to take more than 25% of the total car market by 2020. Other sources have other estimations [4]-[6]. For example, [4] indicates that EV penetration is expected to be 35%, 51%, and 62% by 2020, 2030, and 2050 respectively.

A large proportion of the EV literature is devoted to the analysis of charging impacts on the power system infrastructures [7]. The impacts of EV charging on the power system voltages and loadings is studied in [8] through a real case in Gothenburg, Sweden. In this study, 100% EV penetration and uncoordinated simultaneous charging of EVs for both commercial and residential areas are investigated. Moreover, this study presents the max-
imum number of EVs that can be accommodated by the power system without exceeding the acceptable loadings and voltage deviations. The incremental investments and maintenance cost associated with additional EV load demand is studied in [6]. This study includes on-peak charging, simultaneous off-peak charging and uniformly distributed off-peak charging for three levels of EV penetrations. Impacts of EV charging on power system losses are investigated in this research as well. [9] presents the impact analysis of EV charging on the power system peak load for various charging scenarios. The presented charging scenarios include a novel smart charging which minimizes the peak load.

One of the main components of power system is distribution transformer. Maintaining the safe operation of DTs is crucial for power system stability and reliability. Some of the previous research on impact of EVs on power system corresponds to analysis of EV charging on DTS [10]. A thermal model of transformer is presented in [11] and the impacts of EV charging on DTs’ lifetime is studied. The batteries state of charge before and after charging is incorporated in this study as well. The possible impacts of EV charging on the power system harmonics and overloading are evaluated in [12]. Considering the relation of DTs lifetime with ambient temperature, this research also investigates charging of EVs based on the ambient temperature and daytime.

2.2 Coordination of EV Charging

Previous works on EVs demonstrate the negative impacts of EV charging on loadings, losses, power factors and voltage deviations of different part of power system. Sometimes, the power system is unable to accommodate a large number of EVs without violating the stability and reliability standards. To increase the capacity of power system for accommodating EVs, lots of research has been conducted on controlling of EV charging. Coordinated EV charging reduces the negative impacts of EVs and enables higher EV penetrations in the power system. [13] proposes a demand response program for EVs which maintains the peak load constant. In this program, each vehicle is charged based on the priorities defined by the users. The impacts of the proposed program on the users’ comfort are evaluated through defining some comfort level indices. A real-time smart load management algorithm for coordinated EV charging is presented in [14]. In this algorithm, the sensitivity of system losses to each EV charger at different nodes is calculat-
ed and the charging schedules are determined through a maximum sensitivity selection approach.

The load management programs presented in [13] and [14] decrease the negative impacts of EV charging by coordinating the EV charging. However, the charging schedules developed by these programs are not the optimal charging schedules and the impacts of EV charging can be reduced even more by employing some optimization algorithms. The demand response program presented in [13] can successfully maintain the peak-load constant for 3.3% and 6.6% EV penetrations. However, the effectiveness of this program for higher EV penetrations should be examined as well. The effectiveness of the management algorithm presented in [14] is demonstrated through comparison with uncoordinated EV charging. However, for better evaluation, the proposed program should be compared with other management programs too.

Optimization of load demand in real-time pricing maximizes the users’ benefits and power system stability. The optimal load control programs can be used for EVs to minimize the negative impacts on power system and also users’ electricity payments [15]-[17]. [18] presents a novel demand response model which minimizes the users’ electricity costs. The proposed model optimizes the electricity usage at each hour by using the electricity price at the current hour along with predicting the electricity price at the upcoming hours. Stochastic programming is employed in [19] for developing a novel energy management program for large users. In this study, bilateral contracts, self-production, and pool are considered as three supply sources and risk aversion is incorporated in the program as well. [20] presents an optimal load control for residential loads including EVs which minimizes the users’ electricity payments and waiting time. In this program, the electricity price is predicted based on historical data. The impacts of EV charging on the losses and voltage deviations of the power system are studied in [21]. Moreover, quadratic programming along with dynamic programming are used for coordinating the EV charging and minimizing the power system losses.

2.3 Application of PMSM in EVs

Application of permanent magnet synchronous motors (PMSMs) in various fields of industry, household appliances and electric vehicles is expanding rapidly due to their nu-
merous advantages over other conventional machines. Comparing with induction motors, use of the permanent magnets in the rotor of the PMSM eliminates the magnetizing current. As a result, the power factor is higher for this type of machine. Furthermore, in a PMSM, the DC excitation along with the additional reluctance torque, produced by the saliency, results in a higher output torque and power density. The advantage of the PMSMs over synchronous motors is the elimination of the DC winding in the rotor which prevents rotor losses and brush maintenance. Finally, reluctance and hysteresis motors have lower efficiency, power factor and output torque in spite of the simplicity of their rotor construction.

Application of PMSM in electric vehicles is well investigated in literature [22]-[28]. There are various areas of research in literature associated with application of PMSM in EVs including control of PMSM drive in EVs [22], and [23], designing PMSMs which are suitable for EVs [24] and [25], thermal analysis of PMSM and design of cooling systems for EV applications [26] and [27], and etc. In electric vehicles, control of PMSM drive based on the PMSM efficiency decreases the vehicle’s daily load demand. Efficiency-optimized vector control of PMSM through gradient search technique and golden section technique is presented in [28]. Developing other efficiency-optimized controllers for PMSMs would be beneficiary in reducing EV daily load demand. The first step in developing an efficiency-optimized controller is to accurately model PMSM performance at steady state conditions.

2.4 Accurate Modeling of PMSM

Steady state performance analysis of the PMSM can be achieved by developing an efficient model which describes the performance of the machine based on the principles of its operation. Modeling of the PMSM simplifies the calculations and results in estimating various operating factors including the power factor, efficiency, and torque angle. Although a model which is developed for a specific PMSM can mostly be used for other PMSMs of the same type, the parameters which are employed in the model are distinctive for each machine and should be determined individually. Precise calculation of a PMSM’s performance involves the development of an accurate model along with precise determination of its parameters and characteristics. Various methods have been proposed
recently for improving the accuracy of the PMSM model including consideration of the saturation and core losses. Incorporating the saturation saliency in the modeling of a PMSM facilitates accurate sensorless rotor positioning and high performance of the motor drive. Since the saturation saliency creates nonlinearity in the system of flux equations, an effective modeling of the saturation saliency which simplifies the computations without impeding the satisfactory accuracy is essential [29]. The effect of saturation is modeled in [30] by defining the PMSM inductances as a polynomial function of current and a Fourier series of rotor angle. Analytical models of the PMSM including the saturation saliency in both the rotor reference frame and the stationary reference frame are presented in [31]. The saturation and cross-saturation effect on the PMSM modeling is investigated in [32]. The latter study is performed in the rotor reference frame and for the rotor positioning applications.

Accurate modeling of the core losses is crucial for efficiency analysis and cooling system design. Analytical calculation of the core losses solving Maxwell flux equations disregards the saturation saliency [33]. Numerical methods using Finite Element Analysis are time consuming in spite of their high accuracy. The magnetic equivalent circuit neglects the harmonic linkage flux in the core loss calculation. However, measurement of the core losses eliminates the complex computations and provides the desired accuracy [34]. [35] presents a comparative study of the different analytical models representing core losses in PMSMs. According to [36], the effect of the harmonic linkage flux on core losses can be modeled with the harmonic inductances in the PMSM equivalent circuit. A detailed magnetic equivalent circuit of the PMSM is proposed in [33] for accurate modeling of the teeth flux distribution. The precise determination of the flux distribution contributes to accurate calculation of core losses.

2.5 PMSM Parameter Determination

Developing an accurate model which includes all the characteristics of the PMSM contributes to its precise performance calculation. However, in some cases, the inaccuracy in determining the PMSM parameters is the major factor of the calculation’s imprecision. Unlike conventional synchronous machines, the PMSMs do not have a plethora of literature, standards and patents for parameter determination. The conventional methods
of parameter determination for wound field synchronous machines are not applicable to PMSM due to lack of access to field circuit. Besides, the high centrifugal forces to which the magnets are subjected limit the speed range of some types of PMSMs including surface-mounted PMSM. For these types of PMSMs, flux weakening control is not common in the design of drive/controller and the PMSM is mostly operated at zero d-axis current (space vector control). Consequently, the methods of parameter determination with variable d-axis current are not applicable to these types of PMSM. For these reasons, determining the parameters of a PMSM with the desired level of accuracy may encounter several complexities. Since it is likely to have error in the determination of the PMSM parameters, studying the effect of the parameters’ inaccuracy on the performance calculations is crucial. Although there are enormous investigations on studying the effect of model accuracy on the PMSM performance calculations, inadequate research is dedicated to parameter sensitivity analysis of the PMSM performance. The parameters sensitivity to temperature, saturation and irreversible demagnetization is studied in [37] for an Interior PMSM. However, it does not provide numerical demonstrations and comparative analysis of various parameters’ sensitivity. [38] applies the sensitivity analysis for parameter estimation of an induction machine. Application of the proposed method to the PMSM can be beneficiary in the parameters determination. A comparative analysis of the efficiency sensitivity to various parameters of electrical machines is presented in [39].

Several methods to determine the PMSM’s parameters and characteristics have been proposed recently. The on-line identification of the parameters is an effective method as most of the PMSM parameters vary at different operating conditions [40]. However, on-line identification usually leads to complex calculations using advanced numerical methods such as the Recursive Least-Square Method [41], [42], Marquardt’s algorithm [43], and output-error estimation algorithm [44]. To simplify the calculations, several off-line methods are presented in the literature. The presented methods are simpler, easier to apply, and do not have the convergence difficulties. Finite Element Analysis of the PMSM results in the accurate determination of the parameters [45], [46]. However, initial design of the Finite Element model involves detailed information about the motor specifications and its geometry.
Chapter 3

3 IMPACTS OF EV CHARGING ON TRANSFORMERS

One of the major components of the power system is the distribution transformer. The current harmonics which are produced by EV battery chargers create additional loss in transformer. Consequently, the transformer temperature increases thus reducing its lifetime significantly. Studying the effect of the current harmonics on the lifetime of distribution transformers is essential for grid design and maintenance.

In this chapter, the potentials for EVs to penetrate the transportation market are studied and the additional load required for charging EVs is estimated. Moreover, loss and thermal modeling of transformers including the harmonics are thoroughly discussed. A sample 100 kVA distribution transformer is investigated for studying the impacts of EV penetration on DTs and the ability of the existing power system to accommodate the new EV load demand is evaluated based on calculation results. The estimations and predictions presented in this chapter enable the utilities and government organizations to take necessary precautions. Technical standards and trade regulations are advised by the authors to govern the safety operation of distribution transformers.
3.1 Load Demand for EVs

Recent studies on EV market demonstrate the increasing demand for this new technology. The government politics along with consumers’ interest in the environment protection contributes to the rapid growing of EV market. In addition, as the gas prices continue to rise and the cost of EV battery production declines, the application of EVs becomes more economical and beneficial.

The EV market has the potential to take more than 25% of the entire car market in the United States [47]. Using a conservative estimate, [1] predicts that by 2020, the EV market reaches its potential and one fourth of the car market will be electrified. Consequently, the load demand for battery charging will increase significantly. The EV battery chargers are non-linear loads and their large-scale applications can cause destructive impacts on the power quality of distribution system. The EV load demand when 25% of the car market is electrified is estimated in this section.

Lead-acid and lithium-ion batteries are the leading technologies due to their performance, safety, lifetime and cost. The charging profiles of these two types of batteries are presented in Fig. 3.1. For simplicity of calculations, the charging profiles are fitted with step functions as illustrated in Fig. 3.1.

According to the American driving pattern reported by EPRI [1], on average, half of the cars on US roads drive a maximum of 25 miles per day. Therefore, to have a conservative estimate, this thesis assumes that the average daily travel distance per EV is 25 miles. Considering the energy consumption ratio of EVs [47], and [48], the average electrical energy consumption of battery chargers is 8 kWh per day. The EV battery population is assumed to consist of 60% lithium-ion batteries and 40% lead-acid batteries [9]. Therefore, the average daily charging profile of a single battery can be calculated as presented in Fig. 3.2(a).

According to [49], there are currently a total of 137.11 million cars in the United States. Therefore, number of EVs is expected to reach 34.27 million when EVs comprise 25% of the car market.
The fixed electricity rate, time-of-use electricity rate and real-time electricity rate are the major electricity rate structures in literature and in practice. In this chapter, the time-of-use electricity rate structure is used in the investigations. In the time-of-use structure, the electricity price during the off-peak load hours (9pm to 7am) is less than the peak load hours (7am to 9pm). For simplicity, this paper assumes that all of the EV consumers start charging their batteries at 9pm in the time-of-use structure. The total load demand of EV
battery chargers at 25% EV penetration is estimated in Fig. 3.2(b). It can be noted that the load demand for EV battery charging has the potential to reach 80 GW. According to US Federal Energy Regulatory Commission report [50], the US average load demand in 2011 is approximately 476 GW. Therefore, the load demand for battery charging has the potential to constitute almost 14% of the total load demand during the off-peak hours.

Fig. 3.2. The charging profile and load demand of EV batteries. (a) Average daily charging profile of a single battery. (b) The total load demand of EV battery chargers at 25% EV penetration.
3.2 Modeling of Transformers

EV battery chargers are non-linear loads and connecting them to the distribution system injects harmonics to the grid current. Currently, the load demand of EV battery chargers is a small fraction of the total load demand. Therefore, the harmonic effects of battery chargers are compensated by other linear loads of the distribution system. As discussed in previous section, the EV load demand is increasing rapidly. In future, significant percentage of the total load demand will be allocated to EV battery charging. Consequently, the harmonic impacts of the battery chargers on the power quality of distribution system will be remarkable.

The harmonic distortions produced by EV battery chargers have destructive impacts on distribution transformers. Current harmonics create additional loss in transformer which increases its temperature and reduces its lifetime significantly. To study the effect of current harmonics on distribution transformers, modeling of distribution transformers incorporating grid harmonics is presented in this section.

3.2.1 Loss Model

The transformer loss consists of no-load loss and load loss. The load loss includes the copper losses and stray losses. In dry-type transformers, stray losses are created solely by the eddy currents, whereas in oil-filled transformers, other factors contribute to the stray losses in addition to eddy currents [51]. The load loss of transformers at rated condition is presented in (1). In dry-type transformer, the other stray losses are zero.

\[
P_{LL-R}(pu) = P_{cu}(pu) + P_{EC-R}(pu) + P_{OSL-R}(pu)
\]  

(1)

According to [52], eddy current loss and other stray losses of oil-filled transformer can be obtained by (2).

\[
\begin{align*}
P_{EC-R} &= 0.33 \times (P_{LL-R} - 1) \\
P_{OSL-R} &= 0.67 \times (P_{LL-R} - 1)
\end{align*}
\]

(2)

The distribution transformers supply various types of residential and industrial loads. The non-linearity of their loads inserts high frequency harmonics into the current. To protect the transformer from the destructive impacts of high frequency harmonics, incorpo-
rating the current harmonics in the loss calculations is essential. The per-unit current incorporating the current harmonics is presented in (3).

\[ I_{(pu)} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \left( hI_h / I_1 \right)^2} \]  

(3)

The per-unit copper loss, eddy current loss and other stray losses of the transformer incorporating the current harmonics are expressed in (4) [53].

\[
\begin{align*}
P_{cu(pu)} &= I_{(pu)}^2 P_{cu0(pu)} \\
P_{EC(pu)} &= I_{(pu)}^2 P_{EC-R(pu)} F_{HL} \\
P_{OSL(pu)} &= I_{(pu)}^2 P_{OSL-R(pu)} F_{HL-STR}
\end{align*}
\]

(4)

For calculating \( F_{HL} \) and \( F_{HL-STR} \), (5) can be used [52], [54], [55]. As the other stray losses are zero for dry transformers, \( F_{HL-STR} \) is not defined for this type.

\[
F_{HL} = \frac{\sum_{h=1}^{h_{\text{max}}} (hI_h)^2}{\sum_{h=1}^{h_{\text{max}}} I_h^2} ; \quad F_{HL-STR} = \frac{\sum_{h=1}^{h_{\text{max}}} I_h^2 0.8}{\sum_{h=1}^{h_{\text{max}}} I_h^2}
\]

(5)

The load loss of the transformer incorporating the current harmonics is presented in (6) [56].

\[ P_{LL(pu)} = I_{(pu)}^2 \left( 1 + P_{EC-R(pu)} F_{HL} + P_{OSL-R(pu)} F_{HL-STR} \right) \]  

(6)

3.2.2 Thermal Model

Almost 50% lifetime reduction in transformers is caused by the heat tensions which are created by non-linear loads. Therefore, thermal analysis of the transformers under non-sinusoidal current is crucial.

The temperature rise of the top-oil over ambient temperature can be obtained by (7) [57]. In the dry transformer, top-oil rise temperature is not defined.

\[ \theta_{TO} = \theta_{TO-R} \times \left( \frac{P_{LL(pu)} + P_{NL(pu)}}{P_{L0(pu)} + P_{NL(pu)}} \right)^{0.8} \]

(7)
The temperature rise of the hottest-spot conductor over top-oil temperature can be obtained by (8).

$$\theta_g = (\theta_w - \theta_{TO - R}) \times \left( \frac{P_{LL}(pu)}{P_{LL - R}(pu)} \right)^{0.8}$$

(8)

The temperature of the transformer hottest-spot is expressed in (9). In this equation, $\theta_A$ is the ambient temperature.

$$\theta_H = \theta_{TO} + \theta_g + \theta_A$$

(9)

Aging acceleration factor is a coefficient which represents the effect of hottest-spot temperature on the transformer lifetime as presented in (10). According to [58], the transformer is operating in the safe zone if its aging acceleration factor is smaller than one. The rate of aging is accelerated beyond normal if the aging acceleration factor is larger than one.

$$F_{AA} = \exp \left( \frac{1500}{383} - \frac{1500}{\theta_H + 273} \right)$$

(10)

### 3.2.3 Maximum Permissible Current

The transformer maximum permissible current is the maximum current that can pass through the transformer without causing any notable effect on its real life. Calculating the MPC enables the grid utility to protect the transformer from the lifetime reduction by limiting its maximum current. The maximum permissible current of the dry and oil-filled transformers can be calculated by (11) [59], [60].

$$I_{\text{max}(pu)} = \sqrt{\frac{P_{LL - R}(pu)}{1 + F_{HL} \times P_{EC - R}(pu) + F_{HL - STR} \times P_{OSL - R}(pu)}}$$

(11)

### 3.3 Incorporating EV penetration in Transformer Model

$F_{HL}$ and $F_{HL-STR}$ are the harmonic loss factors for eddy current loss and other stray losses. They incorporate the effect of current harmonics on the load loss. According to (5), for calculating $F_{HL}$ and $F_{HL-STR}$, the harmonics of the current passing through the transformer are required. The transformer current includes the charging current along with the current flowing through other residential and industrial loads. Accordingly, the
harmonics of the transformer current is a combination of the charging harmonics and the harmonics of the current passing through other conventional loads. Calculation of $F_{HL}$ and $F_{HL-STR}$ incorporating the EV penetration is presented in (12).

$$F_{HL} = \sum_{n=1}^{n_{\text{max}}} \left( P_{EV} I_{n-ev} + (1 - P_{EV}) I_n \right)^2 n^2 \left( \sum_{n=1}^{n_{\text{max}}} \left( P_{EV} I_{n-ev} + (1 - P_{EV}) I_n \right)^2 \right)$$

$$F_{HL-STR} = \sum_{n=1}^{n_{\text{max}}} \left( P_{EV} I_{n-ev} + (1 - P_{EV}) I_n \right)^2 n^{0.8} \left( \sum_{n=1}^{n_{\text{max}}} \left( P_{EV} I_{n-ev} + (1 - P_{EV}) I_n \right)^2 \right)$$

(12)

### 3.4 Calculations and Experimental Results

In this section, the impacts of additional EV load demand on load loss, temperature and aging acceleration factor of a sample 100 kVA Iran Transfo distribution transformer is estimated. The ratings and specifications of the investigated DT, as disclosed by the manufacturer, are presented in Table I.

<table>
<thead>
<tr>
<th>Transformer Type</th>
<th>Oil-filled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load loss, $P_{LL}$</td>
<td>600 W</td>
</tr>
<tr>
<td>No-load loss, $P_{NL}$</td>
<td>340 W</td>
</tr>
<tr>
<td>Copper loss, $P_{cu}$</td>
<td>168.2 W</td>
</tr>
<tr>
<td>Rated apparent power, $Q_n$</td>
<td>100 kVA</td>
</tr>
<tr>
<td>Primary voltage, $V_1$</td>
<td>20 kV</td>
</tr>
<tr>
<td>Secondary voltage, $V_2$</td>
<td>400 V</td>
</tr>
<tr>
<td>Primary resistance, $R_1$</td>
<td>10.075 Ω</td>
</tr>
<tr>
<td>Secondary resistance, $R_2$</td>
<td>4.03 Ω</td>
</tr>
<tr>
<td>Ambient temperature, $\theta_A$</td>
<td>40° C</td>
</tr>
<tr>
<td>Rated top-oil temperature rise, $\theta_{TO}$</td>
<td>55° C</td>
</tr>
<tr>
<td>Rated winding temperature rise, $\theta_w$</td>
<td>65° C</td>
</tr>
</tbody>
</table>
The harmonics of charging current is obtained through experimentation on a sample Quick 7212 HF/PFC battery charger. The investigated battery charger and its corresponding lead acid battery packs are illustrated in Fig. 3.3. The charging current and voltage of the battery charger at the end of charging is presented in Fig. 3.4. The harmonic distortions of the charging current can be noted in this figure.

The harmonic distortion of charging current corresponds to the state-of-charge. Generally, the total harmonic distortion (THD) of charging current at the beginning of charging is smaller than the current THD at the end [57]. However, this thesis neglects the effect of state-of-charge on the harmonic spectrum of charging current and considers it to be constant during the charging time. The current harmonic spectrum of the investigated battery charger is presented in Fig. 3.5. The Fluke 434 Power Quality Analyzer is used for measuring the current and voltage harmonics up to the 50th order.

Fig. 3.3. The experimental set-up for an in-house electric vehicle to measure harmonics of charging current.
Fig. 3.4. The measured current and voltage of the battery charger.

Moreover, a set of conventional household appliances including lamps, computers, and etc. is used as a sample for measuring the harmonics of grid current as presented in Figure 3.6.
Fig. 3.6. Harmonic spectrum of the grid current obtained from the sample set of conventional household appliances.

Considering California daily load profile [61] and USA average load demand in 2011 [50], USA daily load profile in 2011 is approximately estimated as illustrated in Fig. 3.7.

Fig. 3.7. Approximated USA daily load profile in 2011.
Using the EV load demand presented in Fig. 3.2, USA daily load profile, the harmonics of the charging current and grid current, $F_{HL}$ and $F_{HL-STR}$ is calculated. Consequently, the eddy current loss, other stray losses, and load loss are obtained as presented in Fig. 3.8. According to this figure, the transformer losses increase significantly due to EV charging specially between 9\text{pm} and 2\text{am}. The transformer load loss reaches its maximum value at 1:30\text{am}.

Top-oil rise, hottest-spot conductor rise, and hottest spot temperatures of the investigated distribution transformer are presented in Fig. 3.9.

Fig. 3.10 illustrates the aging acceleration factor of the distribution transformer including the additional EV load demand. According to this figure, the aging acceleration factor is larger than one during the charging hours and the distribution transformer is not operating in the safe zone. This indicates that the existing power system is unable to accommodate the new EV load demand unless necessary precautions are taken. In this regard, technical standards are recommended for regulating the harmonics of the grid. Moreover, smart EV charging can be used for optimizing the EV load demand and minimizing its negative impacts on DTs.
Fig. 3.8. Effect of additional charging load on the losses of the investigated transformer. (a) Eddy current loss and other stray losses. (b) Load loss.
Fig. 3.9. Effect of additional charging load on the temperature of the investigated transformer. (a) Hottest-spot conductor rise and top-oil rise temperatures. (b) Hottest spot temperature.

Fig. 3.10. Effect of additional charging load on aging acceleration factor of the investigated transformer.

Figure 3. 11 presents the average of the load loss components during the charging period for various EV penetrations. According to this figure, the rate of increase in other stray losses is more than eddy current loss. Therefore, the effect of EV penetration on other stray losses is more than eddy current loss. For the investigated transformer, the other stray losses constitute the largest portion of the load loss.
The average of top-oil rise, hottest-spot conductor rise and hottest-spot temperatures during the charging period for various EV penetrations are illustrated in Fig. 3.12. The slope of top-oil-rise curve is larger than the slope of hottest-spot conductor rise curve. Therefore, the effect of EV penetration on top-oil temperature is more than its effect on hottest-spot conductor temperature.
The average and maximum of aging acceleration factor during the charging hours for different EV penetrations is illustrated in Fig. 3. 13. According to this figure, the maximum of aging acceleration factor is larger than one when more than 20% of the car market is electrified. Therefore, for safe operation of distribution transformers, EV penetration should not exceed 20%.

Fig. 3.13. Average and maximum of aging acceleration factor during the charging period for various EV penetrations.
4 OPTIMIZATION OF CHARGING SCHEDULE

In this chapter, the EV charging load is formulated as an optimization problem. Description of solving the developed optimization problem using Newton Method and also Karush-Kuhn-Tucker (KKT) conditions is explained. Solving the optimization problem by Newton method, the optimal EV charging schedule is proposed. To validate the effectiveness of the proposed charging schedule, the harmonic impacts of EV penetration on a sample 100 kW distribution transformer under two different scenarios will be studied. The first scenario investigates uncontrolled off-peak EV charging when time-of-use electricity pricing is employed [9]. The second scenario considers smart EV charging in a real-time electricity pricing environment. In the second scenario, the EV users charge their batteries in accordance with the proposed charging schedule. For implementing the optimal charging schedule, smart systems in an RTP environment can be used. In this section, a novel smart system which is suitable for EV battery chargers is developed as well.

4.1 The Optimization Problem

In this section, the life time reduction of DTs due to EV charging load is formulated as an optimization problem. Solving the proposed optimization problem enables the utilities and government organizations to calculate the optimized schedule of EV battery charging
with minimum harmful impacts on distribution transformers. The optimized EV charging schedule can be employed by the utility through an effective demand management program based on real-time electricity pricing. In other words, the EV users can be encouraged by financial incentives to charge their EVs in accordance with the optimized charging schedule.

According to (9), for minimizing the aging acceleration factor, the hottest-spot temperature should be minimized. Since the hottest spot temperature changes with respect to the EV penetration at different hours of the charging period, the objective is to minimize the average of hottest-spot temperature over the charging period. Considering the thermal model of the transformer presented in (7)-(9), the average of hottest spot temperature can be minimized by minimizing the average of load loss over the charging period. Therefore, the load loss average should be minimized for optimizing the EV charging schedule.

According to (6), for minimizing the load loss average, the average of $F_{HL}$ and $F_{HL-STR}$ over the charging period should be minimized simultaneously. (13) presents the average of $F_{HL}$ and $F_{HL-STR}$.

$$F_{HL} = \frac{1}{24} \sum_{h=1}^{8} \left\{ \frac{n_{max}}{n_{max}} \left[ \rho^h I_{ev-n} + (1 - \rho^h) I_{n} \right]^2 n^2 \right\}$$

$$F_{HL-STR} = \frac{1}{24} \sum_{h=1}^{8} \left\{ \frac{n_{max}}{n_{max}} \left[ \rho^h I_{ev-n} + (1 - \rho^h) I_{n} \right]^2 n^{0.8} \right\}$$

Equation (14) presents the EV penetration vector which is defined for calculating the optimized EV charging schedule. The components of the EV penetration vector are the optimized EV penetrations at different hours of the charging period.

$$\psi = \left\{ \rho^1, \rho^2, ..., \rho^8 \right\}$$

The total load required in one day for charging EVs corresponds to the total number of EVs and their daily energy consumption. The optimized charging schedule should provide the daily EV load demand. Therefore, the hourly EV penetrations are constrained by equality constraint presented in (15).
\[
\frac{1}{8} \sum_{h=1}^{8} \rho^h = P_{EV}
\]  

(15)

The inequality constraints on the hourly EV penetrations are presented in (16).

\[
0 \leq \rho^h \leq 1 \quad \forall h \in H
\]  

(16)

As mentioned before, for maximizing the transformer life time, the average load loss should be minimized. Using the load loss equation presented in (6) and the average of \( F_{HL} \) and \( F_{HL-STR} \) expressed in (13), the objective function for maximizing the transformer life time can be derived as presented in (17). The optimization problem is to minimize the objective function.

\[
f(\Psi) = \frac{8}{\sum_{h=1}^{8} P_{EC-R}(pu)} \left( \frac{n_{\text{max}}}{\sum_{n=1}^{n_{\text{max}}}} \left( \rho^h I_{ev-n} + \left(1 - \rho^h\right) I_{n}^h \right)^2 n^2 \right) \\
+ \frac{8}{\sum_{h=1}^{8} P_{OSL-R}(pu)} \left( \frac{n_{\text{max}}}{\sum_{n=1}^{n_{\text{max}}}} \left( \rho^h I_{ev-n} + \left(1 - \rho^h\right) I_{n}^h \right)^2 n^{0.8} \right)
\]  

(17)

The coefficients of the optimization function are constrained by (18).

\[
\begin{aligned}
0 \leq I_n^h, I_{ev-n} &\leq 1 \quad \forall h \in H, \forall n \in N \\
0 \leq P_{EC-R}, P_{OSL-R} &\leq 1
\end{aligned}
\]  

(18)

4.2 Karush-Kuhn-Tucker conditions

An effective technique for solving the optimization problem is to incorporate the equality and inequality constraints in the optimization function. In this section, the constraints are included by converting the optimization problem to its Lagrange dual description. We refer to the optimization function presented in (15) as the primal function. The Lagrangian associated with the primal problem is presented in (19), [62].

\[
L(\Psi, A, B, \nu) = f(\Psi) + \sum_{h=1}^{8} \left( \nu \rho^h \right) - 24\nu P_{EV} + \sum_{h=1}^{8} \left( \alpha^h \rho^h \right) + \sum_{h=1}^{8} \left( \beta^h - \beta^h P_{EV} \right)
\]  

(19)
where \( A \) and \( B \) are the lagrangian multiplier vectors as expressed in (20) and they are associated with the lower and upper bound constraints respectively.

\[
A = \{ \alpha^1, \alpha^2, \ldots, \alpha^8 \} \quad \text{and} \quad \alpha^h, \beta^h \quad \forall h \in H \tag{20}
\]

The Lagrange dual of the primal function is expressed in (21) [63]. According to this equation, the Lagrange dual of the primal problem, is the minimum of Lagrangian associated with the primal problem for all values of \( \Psi \).

\[
k(A, B, \nu) = \inf_{\Psi} L(\Psi, A, B, \nu) \tag{21}
\]

The Lagrange dual problem is to maximize the Lagrange dual function when the optimization variables are Lagrangian multipliers. In this section, the KKT optimality conditions are employed for solving the optimization problem. In order to satisfy the KKT conditions, it is necessary to meet the strong duality condition [64]. The strong duality holds when the optimal values of the Lagrange dual problem and primal problem are equal as presented in (22).

\[
\sup_{A,B,\nu} k(A, B, \nu) = \inf_{\Psi} f(\psi) \tag{22}
\]

Once the strong duality condition is satisfied, one can calculate the optimal points of the primal and dual problem by solving the system of equations presented as Karush-Kuhn-Tucker optimality conditions in (23).

\[
\begin{align*}
\nabla L(\Psi, A, B, \nu) &= 0 \\
8 \sum_{h=1} \rho^h &= 24PEV \\
\alpha^h \rho^h &= 0 \quad \forall h \in H \\
\beta^h (\rho^h - PEV) &= 0 \quad \forall h \in H
\end{align*} \tag{23}
\]

The KKT conditions associated with the constraints of primal and dual optimization variables are presented in (24).

\[
\begin{align*}
0 \leq \alpha^h, \beta^h \quad \forall h \in H \\
0 \leq \rho^h \leq 1 \quad \forall h \in H
\end{align*} \tag{24}
\]

Although the optimal points of primal and dual problems necessarily satisfy the KKT conditions, meeting the KKT conditions is not sufficient for being the optimal points. To
ensure that the solution to the KKT conditions is the optimal points of primal and dual problems, the objective function needs to be convex. In other words, when the objective function is convex, the KKT conditions are sufficient for the points to be optimal. Solving the system of equations presented in (23) yields the optimal charging schedule. The proposed charging schedule minimizes the destructive impacts of EV charging on distribution transformers and protects them from life time reduction.

4.3 Newton Method

The proposed optimization problem can be solved using the Newton Method. In this method, a sequence of EV penetration vectors are generated which converges to the optimal EV penetration vector through iteration. The sequence of EV penetration vectors is presented in (25).

\[ \Psi^{k+1} = \Psi^k + \omega_k \nu_N \]  

(25)

Where \( \nu \) is the search direction, \( \omega \) is the step size and \( k \) is the iteration number. At each step, the search direction is calculated using the second order Taylor expansion of the objective function as presented in (26) [64].

\[ \min_{\nu_N} f(\Psi + \nu_N) = f(\Psi) + \nabla f(\Psi)^T \nu + \frac{1}{2} \nu_N^T \nabla^2 f(\Psi) \nu_N \]  

(26)

To satisfy the equality constraint of the optimization problem, the entries of the search direction is constrained by (27).

\[ \frac{1}{8} \sum_{h=1}^{8} (\nu_N^h + \nu_E^h) = P_{EV} \Leftrightarrow \sum_{h=1}^{8} \nu_N^h = 0 \]  

(27)

Simplifying the equation presented in (26), the search direction can be calculated by (28).

\[ \min_{\nu_N} \nabla f(\Psi)^T \nu_N + \frac{1}{2} \nu_N^T \nabla^2 f(\Psi) \nu_N \]  

(28)

To satisfy the equality constraint of the optimization problem, sum of all entries of the search direction should be zero. The step size is calculated using the backtracking line search. In this method, at each step, the step size is multiplied by a constant as long as the conditions presented in (29) are satisfied. In this equation, \( \alpha \) is a constant between zero and 0.5.
\[
f(\Psi) + \alpha_N \omega_N \nabla f(\Psi)^T \nu \prec f(\Psi + \omega_N \nu_N) \]
\[
0 \leq \Psi + \omega_N \nu_N \leq 1
\]  
(29)

The stop criterion of the iterations is defined by the Newton decrement presented in (30). If the Hessian matrix is not positive semi definite, the gradient projected onto the null space of the active set can be used as the stop criterion.

\[
\lambda_N = \sqrt{\nabla_N^T \nabla^2 f(\Psi) \nu_N}
\]  
(30)

The diagrammatic representation of Newton method is illustrated in Fig. 4.1.

**4.4 Calculated Results**

In this section, the proposed optimization problem is solved and the novel load management program for electric vehicles is developed. Newton Method is investigated for solving the optimization problem and MATLAB software is used for performing the corresponding calculations and computations. Figure 4.2 presents optimal charging schedule for EVs which minimizes the life time reduction of DTs. According to this figure, unlike uncontrolled off-peak charging, smart EV charging provides an optimal load profile for electric vehicles which perfectly corresponds to the load profile of other loads in the grid. As illustrated in Fig. 4.2, from 9pm to 12am, the load demand for other loads is higher. Therefore, the optimal EV load demand during these hours is zero. Whereas, from 2am to 4am, the load demand for conventional loads is minimum and consequently the optimal load demand for EVs is maximum.

In order to evaluate the effectiveness of the proposed charging schedule, the effect of EV charging on a sample distribution transformer is studied under two different scenarios. The first scenario investigates uncontrolled off-peak EV charging when time-of-use electricity pricing is employed [6]. The second scenario considers smart EV charging in a real-time electricity pricing environment. In the second scenario, the EV users charge their batteries in accordance with the optimal charging schedule proposed in the previous section. Figure 4.3 presents the calculated load loss of the sample transformer under the investigated scenarios. As illustrated in this figure, smart EV charging reduces the transformer load loss significantly.
Fig. 4.1. Diagrammatic representation of Newton method for optimizing the EV charging schedule.
Fig. 4.2. Optimal charging profile for EVs based on minimization of DTs’ aging acceleration factor.

Fig. 4.3. Calculated load loss of the sample transformer for smart EV charging and uncontrolled off-peak charging.

The calculated hottest spot temperature of the sample transformer under the investigated scenarios is presented in Fig. 4.4. According to this figure, the maximum hottest-
spot temperature for smart EV charging is 104.5 °C; whereas the hottest spot temperature increases up to 112.3 °C when uncontrolled off-peak charging is investigated.

Figure 4.4. Calculated hottest-spot temperature of the sample transformer for smart EV charging and uncontrolled off-peak charging.

Figure 4.5 presents the calculated aging acceleration factor of the investigated transformer for both smart charging and uncontrolled off-peak charging. As illustrated in this figure, the aging acceleration factor for smart EV charging is always smaller than one. Therefore, the optimized charging schedule perfectly protects the sample transformer from life time reduction and maintains its safe operation during the charging hours.

The optimal load demand for electric vehicles at different EV penetrations is presented in Fig. 4.6. According to this figure, for lower EV penetrations the optimal EV load demand at the beginning of charging hours is zero. As EV penetration increases, the optimal EV load demand at the beginning of charging hours increases.
Fig. 4.5. Calculated aging acceleration factor of the sample transformer for smart EV charging and uncontrolled off-peak charging.

Fig. 4.6. Optimal load demand for electric vehicles at different EV penetrations.

The average of load loss components during the charging hours for different EV penetrations is presented in Fig. 4.7. In Fig. 4.8, the average of transformers temperatures for both smart charging and uncontrolled off-peak charging is illustrated. According to these
figures, the load loss and hottest-spot temperature for smart EV charging is remarkably lower than uncontrolled off-peak charging.

![Graph](image)

Fig. 4.7. The average of load loss components during the charging hours for different EV penetrations. (a) Eddy current loss and other stray losses. (b) Load Loss.
Fig. 4.8. The average of transformer temperatures during the charging hours for different EV penetrations. (a) Top-oil temperature and hottest-spot conductor temperature. (b) Hottest spot temperature.

The average and maximum of the aging acceleration factor during the charging hours is presented in Fig. 4.9. According to this figure, the maximum of aging acceleration factor for smart EV charging stays constant for EV penetrations smaller than 55%. At 80%
EV penetration, the aging acceleration factor for smart charging reaches its critical value. Therefore, the existing power system can accommodate up to 80% EV penetration without threatening the lifetime of distribution transformers when the proposed charging schedule is employed. Whereas, with the uncontrolled off-peak charging, the EV penetration is limited to 20% if safe operation of transformers is desired.

![Graph showing the average and maximum of aging acceleration factor for different EV penetrations.](image)

Fig. 4.9. The average and maximum of aging acceleration factor for different EV penetrations.

### 4.5 Smart EV Charging

The load management programs including real-time pricing, day-ahead pricing, and time-of-use pricing contribute to power system reliability and utility economics. Effective design of the load management programs encourages the EV users to shift the EV load to off-peak hours. Consequently, the peak-to-average ratio (PAR) improves.

The real-time pricing offers a time-varying pricing that maximizes the utility benefits and system reliability. The EV users are encouraged to participate in this program by financial incentives. In order to optimize the benefits of the RTP, smart automation systems are utilized for controlling the energy consumption of the battery chargers. Smart
systems enable the EV users to respond effectively to RTP by minimizing their electricity payment and disruption. In this section, a mathematical model for energy consumption of the battery chargers is developed. Optimizing the benefits of the EV users is achieved by formulating the energy consumption model as an optimization problem.

Hourly energy consumption vector, \( X \), is defined for calculating the optimized charging hours of an EV based on the electricity price and waiting cost. The components of the energy consumption vector are the optimized energy consumptions of the battery charger at different hours of the charging period as presented in (31).

\[
X = \begin{bmatrix} x^1, x^2, \ldots, x^8 \end{bmatrix}
\]  

(31)

The total load required in one day for charging an electric vehicle corresponds to the average daily travel distance per EV and energy consumption ratio. The optimized charging schedule should provide the daily EV load demand. Therefore, the hourly energy consumptions are constrained by equality constraint presented in (32).

\[
\sum_{h=1}^{8} x^h = 8
\]  

(32)

The inequality constraints on the hourly energy consumptions are presented in (33).

\[
0 \leq x^h \leq 6.14 \quad \forall h \in H
\]  

(33)

The hourly energy consumptions are also constrained by the charging profile the EV battery. The charging profiles of lead-acid and lithium-ion batteries were previously presented in Fig. 3.1. According to this figure, the hourly energy consumptions of lead-acid batteries are constrained by their charging profile as presented in (34).

\[
0 \leq x^h \leq 6.14 \quad \forall h \in H
\]  

(34)

(35) presents the constraints on hourly energy consumptions of lithium-ion batteries associated with their charging profile.
Solving this optimization problem for EV energy consumption, smart systems can schedule the EV charging hours with minimum electricity payment and waiting time for users.
Chapter 5

5 PMSM Steady-State Modeling

The efficiency of PMSM at different operating condition is determined by its efficiency map. The efficiency maps for surface-mounted and interior-mounted PMSM are presented in Fig. 5.1 [65]. In PMSM efficiency map, each loop represents a series of constant efficiency points and the inner loops have higher efficiencies. Driving the EV motor in the high efficiency zones of the efficiency map increases the efficiency of PMSM and consequently the EV powertrain. Therefore, controlling PMSM based on its efficiency map contributes to reduction in EVs’ daily load demand. Considering the significance of accurate modeling in the control of PMSM, this chapter focuses on accurate modeling of PMSM and the sources of error in PMSM steady-state performance estimation. The research presented in this chapter can be extended to developing an effective PMSM controller for high efficiency applications.

In this chapter, several methods for the PMSM parameters determination with varying level of accuracy are presented. The proposed methods are employed for calculating the output power of a laboratory PMSM and the effect of parameter error on the calculations is studied. An experimental analysis of the output power sensitivity to various parameters is performed. Selecting the appropriate method for parameter determination corresponds to the desired level of accuracy in the calculations, performance sensitivity to the parame-
ters, and practical difficulties of the methods. Practical difficulties include complexity, facility availability, and the PMSM’s structural limitations. Once the appropriate method is designated, one can investigate on increasing the accuracy of the calculations by improving the PMSM model. This thesis presents an accurate model for steady-state analysis of the PMSM including the saturation saliency and core losses. The accuracy of the proposed model is compared with the conventional d- and q-axis model and its higher accuracy is validated through experimental results.

Fig. 5.1. The PMSM efficiency map. (a) Interior-mounted PMSM. (b) Surface-mounted PMSM.
In this chapter, several methods for the PMSM parameters determination with varying level of accuracy are presented. The proposed methods are employed for calculating the output power of a laboratory PMSM and the effect of parameter error on the calculations is studied. An experimental analysis of the output power sensitivity to various parameters is performed. Selecting the appropriate method for parameter determination corresponds to the desired level of accuracy in the calculations, performance sensitivity to the parameters, and practical difficulties of the methods. Practical difficulties include complexity, facility availability, and the PMSM’s structural limitations. Once the appropriate method is designated, one can investigate on increasing the accuracy of the calculations by improving the PMSM model. This paper presents an accurate model for steady-state analysis of the PMSM including the saturation saliency and core losses. The accuracy of the proposed model is compared with the conventional d- and q-axis model and its higher accuracy is validated through experimental results.

5.1 Parameter Determination

The PMSM parameters can be determined either by calculation or measurement. Calculation of parameters utilizes machine geometry and considers the design specifications and configurations. Parameters measurement employs specific experimental tests which are based on the principles of the PMSM operation. Measuring the parameters eliminates the necessity of providing the machine’s dimensions and its configurations. However, designing an appropriate test which suits the machine characteristics and provides the desired level of accuracy requires a significant amount of research.

5.1.1 Calculation of Parameters

Access to the PMSM dimensions and design specifications enables the researchers to determine its parameters without running any experimental test. For deriving all the parameters complete knowledge of the components’ characteristics, their detailed dimensions along with their configurations and structures are required.

Armature Resistance, $R_a$

Calculation of the armature resistance, $R_a$ is necessary for determining the PMSM’s losses and its machine efficiency. At low speeds, the armature resistance can affect the per-
formance of the machine including its power factor and torque angle. The armature winding resistance per phase, neglecting the skin effect, can be calculated by (36).

\[
R_a = \frac{2N\left(L_s + h_M + 2g + \frac{2p\pi}{\pi}\right)}{a\sigma a}
\]  

(36)

**Flux Linkage Constant, \( \lambda_f \)**

Variation of the magnetic flux produced by the permanent magnets induces voltage in the armature windings. Therefore, calculation of the flux linkage is essential for determining the PMSM performance. The flux linkage constant of a PMSM, can be calculated by (37) [66].

\[
\lambda_f = \left(\frac{\sqrt{2}}{\pi}\right)Nk_w\tau L_s \frac{B_r}{1 + \mu rrec \frac{g}{h_M}}
\]  

(37)

**d- and q-Axis Armature Inductances, \( L_d \) and \( L_q \)**

The d- and q-axis armature inductances can be obtained using (38) [67], [69]. In this equation, \( \lambda_{ls} \) is the per-slot leakage permeance and can be calculated based on the slot shape and configuration [66].

\[
L_d = 12\mu_0 L_s N^2 \left[ \lambda_{ls} + \frac{\tau}{5\pi L_s} + \frac{\tau \mu rrec k_w^2}{p(h_M + \mu rrec g)} \times \left\{ \frac{s^2 + 7.2p^2}{15p^2} \sin\left(\frac{\pi p}{s}\right)^2 + \frac{1}{2\pi^2} \right\} \right]
\]

\[
L_q = 12\mu_0 L_s N^2 \left[ \lambda_{ls} + \frac{\tau}{5\pi L_s} + \frac{\tau k_w^2}{pg_q} \times \left\{ \frac{s^2 + 7.2p^2}{15p^2} \sin\left(\frac{\pi p}{s}\right)^2 + \frac{1}{2\pi^2} \right\} \right]
\]  

(38)

**5.1.2 Measurement of Parameters**

For calculating the PMSM parameters, complete information of the machine’s structures and its dimensions is required. Since most of the required dimensional information is usually unknown to the consumers, the determination of the parameters through calculation is not applicable for most cases. Therefore, the machine parameters should be determined by conducting experimental tests.

The conventional method to measure the armature resistance is the DC test. For increased accuracy, the DC voltage can be applied to the machine terminals for the rated current (\( I_{100\%} \)) and 150% of the rated current (\( I_{150\%} \)) while phase ‘b’ and ‘c’ are short cir-
cuited. The armature resistance can be obtained from the ratio of the voltage and the current difference for these two states as described in (39) [70].

\[
R_a = \frac{2}{3} \times \left( \frac{V_{DC-150\%} - V_{DC-100\%}}{I_{DC-150\%} - I_{DC-100\%}} \right)
\] (39)

For measuring the flux linkage constant, the conventional open-circuit test can be employed. The d- and q-axis inductances of the PMSM can be determined either by the standstill tests or by the on-load tests. On-load methods are usually preferable for line-start PMSMs. They have the advantage of considering the effect of saturation and the demagnetizing current on the variation of parameters. For other types of PMSMs, the standstill tests are advantageous due to the PMSMs drive design and starting complications. In this section, novel methods for measuring the d- and q-axis inductances are presented.

The AC standstill test

In the AC standstill test, AC voltage is applied to one phase of the PMSM as illustrated in Fig. 5.2. Measuring the phase voltages and current leads to determination of the self and mutual inductances as expressed in (40) [71].

\[
L_{aa} = \frac{\left[ \frac{V_a}{I_a} \right]^2}{\omega_s} - R_a^2; \quad M_{ac} = \frac{V_c}{\omega_s I_a}
\] (40)

To determine the self and mutual inductances as a function of rotor angle the rotor is aligned in different positions with respect to the phase ‘a’ magnetic axis. For each position, the self and mutual inductances can be obtained by (9). The d- and q-axis synchronous inductances can then be determined from the coefficients of the sinusoidal functions used to fit \(L_{aa}(\theta)\) and \(L_{ca}(\theta)\) as expressed in (41).
The Novel DC Standstill Test

In the DC standstill test, the PMSM is exposed to a step DC voltage and the transient response of the machine is studied. Measuring the transient current response leads to determination of the time constant and consequently, the d- and q-axis inductances as expressed in (42). In this equation, $R_{CKT}$ is the circuit resistance including the resistance of the connections, shunt resistance, and the battery internal resistance.

\[
L_d = \tau_d \left( R_a + \frac{2}{3} R_{CKT} \right) \quad ; \quad L_q = \tau_q \left( R_a + \frac{1}{2} R_{CKT} \right)
\]  

(42)

In a DC test, the d-axis inductance can be measured when the resulting magnetic flux, produced by the armature currents, is aligned with the direct axis; while the q-axis inductance measurement corresponds to the alignment of the resulting armature magnetic flux.

\[
\begin{align*}
L_{aa}(\theta) &= a_0 + a_1 \sin(2\theta) \\
L_{ac}(\theta) &= b_0 + b_1 \sin(2\theta)
\end{align*}
\]

\[
\Rightarrow \begin{bmatrix} L_d = a_0 + \frac{3}{2} a_1 - b_0 \\ L_q = a_0 - \frac{3}{2} a_1 - b_0 \end{bmatrix}
\]  

(41)
flux with the quadrature axis. These two desired conditions can be achieved through the stator connections illustrated in Fig. 5.3 [72]-[74].

![Circuit connection for DC standstill test](image)

Fig. 5.3. Circuit connection for DC standstill test. (a) d-axis inductance measurement. (b) q-axis inductance measurement.

A novel approach for measuring the d- and q-axis inductances is to calculate the magnetic flux based on the variation of the terminal voltage in a specific period of time [75]. Using the set-up illustrated in Fig. 5.3 and measuring the transient terminal voltage and current, the magnetic flux and subsequently, the d- and q-axis inductances of the system can be determined by (43). In this equation, \( h \) is the variable of the integral and represents time, \( \nu(h) \) is the instantaneous terminal voltage, and \( i(h) \) is the instantaneous terminal current of the PMSM.

\[
L_d(t) = \left[ \int_0^t \left( \nu(h) - \frac{3}{2} R_a \times i(h) \right) dh \right] / i(t) \tag{43}
\]

\[
L_q(t) = \left[ \int_0^t \left( \nu(h) - 2R_a \times i(h) \right) dh \right] / i(t)
\]

According to (43), the d- and q-axis inductances are functions of time and can be obtained for different instants within the transient time interval. Moreover, the transient current response provides information about the magnitude of current in the direct and quad-
ature axes for each instant. By combining these two data, one can derive the d- and q-axis inductances as functions of d-and q-axis currents respectively. Since in the DC standstill test, the transient current varies from zero to rated current and higher, this method is able to measure d- and q-axis inductances for a wide current range. In fact, this novel method is proposed by the authors with the purpose of measuring the saturated d- and q-axis inductances at high currents.

The Proposed On-load Test

The PMSM torque angle can be determined at any operating condition if the d-axis inductance is available [76]. The description of calculating torque angle using the d-axis inductance is presented in (44).

\[
B = V_{ph} - \omega_s L_d I_t \sin(\theta) - R_a I_t \cos(\theta) \\
C = \omega_s L_d I_t \cos(\theta) - R_a I_t \sin(\theta)
\]

\[
\Rightarrow \delta = \cos^{-1}\left( \cos \omega \frac{E_f B - \sqrt{B^2 C^2 - C^2 E_f^2 + C^4}}{B^2 + C^2} \right)
\]

(44)

Once the torque angle is determined, the q-axis inductance of a PMSM can be determined by (45).

\[
\delta = \tan^{-1}\left[ \frac{I_t \omega_s L_q \cos \theta - I_t R_a \sin \theta}{V_t + R_a I_t \cos \theta + \omega_s L_q I_t \sin \theta} \right]
\]

(45)

Another approach for measuring d-axis inductance is presented in [77]. In this method, phase ‘a’ current is aligned with the quadrature axis by keeping d-axis stator current equal to zero. The phasor diagram illustrated in Fig. 5.4 can be used to determine the q-axis synchronous inductance as expressed in (46).

\[
L_q = \frac{V_t \sin(\theta)}{I_a \omega}
\]

(46)
5.2 Calculated and Experimental Results

Applying the theoretical methods presented above, the equivalent circuit parameters are determined for a 21 hp laboratory PMSM. The ratings and specifications of the PMSM used in the investigations are described in Table II. The PMSM back EMF obtained from the open-circuit test is presented in Fig. 5.5. Unlike interior PMSMs, the surface-mounted PMSMs have a smooth sinusoidal excitation voltage due to their uniform rotor configuration as illustrated in Fig. 5.5 [78]. The slight distortions in the PMSM’s back EMF possibly attributes to the winding and slotting harmonics.

Fig. 5.4. Phasor diagram of a PMSM in the case of aligning phase ‘a’ current with q-axis for measurement of q-axes inductance.

Fig. 5.5. The PMSM Back EMF and its harmonic distortions.
<table>
<thead>
<tr>
<th>Machine type</th>
<th>Surface mounted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>21 hp</td>
</tr>
<tr>
<td>Rated motor voltage</td>
<td>297 V</td>
</tr>
<tr>
<td>Rated motor current</td>
<td>35 A</td>
</tr>
<tr>
<td>Rated motor speed</td>
<td>3000 r/min</td>
</tr>
<tr>
<td>Number of pole</td>
<td>8</td>
</tr>
<tr>
<td>Height of permanent magnet, ( h_M )</td>
<td>4.15 mm</td>
</tr>
<tr>
<td>Width of permanent magnet, ( w_m )</td>
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</tr>
<tr>
<td>Armature stack effective length, ( L_s )</td>
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</tr>
<tr>
<td>Carter’s coefficient, ( k_C )</td>
<td>1.0297</td>
</tr>
<tr>
<td>Pole pitch, ( \tau )</td>
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</tr>
<tr>
<td>Conductor cross sectional area, ( s_a )</td>
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</tr>
<tr>
<td>Conductor conductivity, ( \sigma )</td>
<td>57 MS/m</td>
</tr>
<tr>
<td>Number of parallel paths, ( a )</td>
<td>3</td>
</tr>
<tr>
<td>Number of turns, ( N )</td>
<td>55</td>
</tr>
<tr>
<td>Stator winding coefficient, ( k_w )</td>
<td>0.96</td>
</tr>
<tr>
<td>Remnant magnet flux density, ( B_r )</td>
<td>0.6 T</td>
</tr>
<tr>
<td>Relative recoil permeability, ( \mu_{rec} )</td>
<td>1.094</td>
</tr>
<tr>
<td>Air-gap length in d-axis, ( g )</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Air-gap length in q-axis, ( g_q )</td>
<td>4.25 mm</td>
</tr>
</tbody>
</table>

The setup platform for DC standstill test is presented in Fig. 5.6. The measurements were performed using a lead acid battery (12 V, 100 Ah), TPS 2024 digital storage oscilloscope, shunt resistor (5 mΩ, 100 A), and a 125 V-175 A breaker. The measured transient current response of the PMSM in a DC standstill test is presented in Fig. 5.7. The battery voltage, shunt voltage and PMSM terminal voltages were measured by the oscilloscope every 20 µs as shown in Fig. 5.8. The transient current obtained from the measured shunt voltage along with the terminal voltage is used in (43) for determining the variation of d- and q-axis inductances in the transient time interval. Consequently, the d- and q-axis inductances for different currents are obtained, as presented in Fig. 5.9.
Fig. 5.6. Experimental setup for measuring d- and q-axis inductances of PMSM through DC standstill test.

\[ i(t) = I_{DC} \left( 1 - e^{-t/\tau} \right) \]

Fig. 5.7. Transient current response of the PMSM in a DC standstill test for both d-axis measurement set-up and q-axis measurement set-up.
Fig. 5.8. Transient response of the PMSM to a step DC voltage for q-axis measurement (a) Variation of battery voltage and shunt voltage for time constant determination. (b) Variation of PMSM terminal voltage and shunt voltage for magnetic flux measurement.
Fig. 5.9. d- and q-axis inductances of the PMSM obtained from magnetic flux measurement. (a) q-axis inductance, (b) d-axis inductance.

The q-axis inductance of the PMSM is measured by employing the proposed on-load test. The value of the d-axis inductance used in the calculations is 1.87 mH, which is obtained from the dimensional information. Figure 5.10 illustrates variation of the q-axis inductance with respect to the q-axis current. The effect of the saturation on the q-axis inductance can be noticed in this figure.
The AC standstill test is not applicable to the PMSM under investigation as its neutral is not accessible. The on-load test using the d-axis current controller was not performed on the experimental PMSM due to the unavailability of the d-axis current controller.

Table III presents the parameters of the PMSM obtained from the proposed methods. According to Table III, some of the methods do not provide the desired level of accuracy in determining the parameters. However, employing these parameters for the performance calculations results in the satisfactory precision as be discussed in the following section.

**TABLE III**

<table>
<thead>
<tr>
<th>Applied method</th>
<th>$\lambda_{d}$ [V.s]</th>
<th>$R_a$ [$\Omega$]</th>
<th>$L_d$ [mH]</th>
<th>$L_q$ [mH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer information</td>
<td>0.136</td>
<td>0.098</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Calculated values</td>
<td>0.147</td>
<td>0.0970</td>
<td>1.87</td>
<td>1.92</td>
</tr>
<tr>
<td>Open circuit test</td>
<td>0.136</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Conventional DC test</td>
<td>-</td>
<td>0.0914</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Modified DC test</td>
<td>-</td>
<td>0.0971</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DC standstill test</td>
<td>-</td>
<td>-</td>
<td>1.60</td>
<td>1.65</td>
</tr>
<tr>
<td>DC standstill test</td>
<td>-</td>
<td>-</td>
<td>1.71</td>
<td>1.78</td>
</tr>
<tr>
<td>On-load test($L_q$ measurement)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.98</td>
</tr>
</tbody>
</table>

Fig. 5.10. q-axis inductance of a PMSM obtained from output power and torque equation in an on-load test.
5.3 Analytical Evaluation of the Presented Methods

To select the most effective method based on needs and demands, one should assess the complexity and accuracy of each method. The complexity of a method can be discussed from the point of view of available information, equipment requirements, practical difficulties of the experiment, etc. In this section, the complexity of the presented methods will be discussed in detail and a comprehensive overview of the sources of error for each method will be introduced for accuracy analysis. Evaluating the merits and demerits of each method, one can choose the best method that corresponds to their desired level of intricacy and precision.

Calculation of Parameters

Calculation of equivalent circuit parameters requires access to dimensions and design specifications of the PMSM. For deriving all the parameters such as armature resistance, d- and q-axis inductances, and leakage inductance complete knowledge of characteristics of the machine components, their detailed dimensions and also their configurations and structures should be determined. Characteristics of the components include permeability information of the stator and rotor core, magnetizing characteristics of the permanent magnets, and also conductivity information of the stator windings. Machine dimensional information includes the air-gap mechanical clearance, detailed dimensions of the slots and permanent magnets, and also the length of the armature winding both inside the slots and at the end connections. Finally, the information about machine design includes rotor configuration, slot shape, and armature winding configuration. Providing machine dimensions requires separating the PMSM stator and rotor, while obtaining characteristics of the machine components requires advanced measuring instruments. However, once all the above-mentioned information for the PMSM is available, all the required parameters can be calculated with this method.
Measurement of Armature Resistance and Flux Linkage

The open-circuit test is a simple and effective method for measurement of flux linkage constant which is applicable to any kind of PMSM. However, since there is no stator current during the machine operation for the test, this method doesn’t consider the effect of demagnetization and flux weakening on the internal voltage. For armature resistance measurement, the conventional DC test can be applied to the PMSM. As the armature resistance is small for most of the PMSMs, the precise measurement of terminal voltage for the currents lower than rated current requires high-accuracy measuring instruments. Therefore, the modified DC test suggests measurement of armature resistance based on voltage to current ratio for rated and 150% of rated current. The experimental results presented in Table III indicate more accuracy for modified DC test comparing to conventional DC test.

DC Standstill Test

DC standstill test is an efficient method for measuring the d- and q-axis inductances which eliminates the use of controllers and complex control algorithms. As the test is performed in standstill condition, the complications of operating the PMSM in a desired status and consequently design of a suitable controller which maintains the desired operating condition for the PMSM is eliminated. However, use of accurate inrush current detectors with small sampling time is mandatory for acceptable accuracy. Measurement of d- and q-axis inductances using the time constant of the system requires the equivalent resistance of the circuit to be determined within an accuracy of 0.01 Ω. Among other sources of error for the DC standstill test, the turn-on time of the switching, the effect of equivalent capacitance of the circuit on the transient behaviour of the system, and the voltage ripple of the battery can be mentioned. Overall, the DC standstill test reduces the complexity of the measurements, while fails to provide high accuracy unless advanced measuring instruments are provided.
AC Standstill Test

The AC standstill test is another approach to measure the PMSM parameters where an AC voltage is injected to a standstill PMSM and the variations in the rms values of terminal voltages and current with respect to rotor position are observed. This method does not require implementation of any controller or the use of inrush current detectors. Moreover, as there are few methods for measurement of leakage inductance, the ability of the AC standstill test in measuring the PMSM leakage inductance is of great value. However, since terminal voltages and currents have slight variation for different rotor position, very accurate devices for AC measurement of voltage and current are needed. In addition, as the number of poles for the PMSM increases, the ratio of the electrical angle to mechanical angle decreases and as a result, adjustment of the rotor position for providing various electrical rotor angles becomes harder and less accurate.

On-load Test

The on-load tests presented in this paper for measurement of q-axis inductance considers the effect of operating condition on variation of the q-axis inductance including the effect of saturation in the quadrature axis. The on-load test using d-axis current controller requires a rotor position sensor for applying the park transformer to terminal currents. The cost of the position sensors along with complications of system control encourages the employment of the second method of on-load test using power and torque angle equations whenever d-axis inductance is available. The latter method is effective for any operating condition and no control strategy is required. Neglecting the reluctance power in the power equation and also the effect of demagnetizing current on internal voltage in the torque angle equation are the most significant sources of error for this method.

5.4 Parametric Sensitivity Analysis

In this section, the effect of the parameters’ accuracy in the precision of the performance calculations is examined through experimental results. Various methods for determining the parameters presented in section 3-1 is used in the conventional d-q axis model for calculating the output power of the laboratory PMSM. The applied methods
have different levels of accuracy and consequently their performance calculations have varying discrepancy with the experimental results. Since for all the methods, the calculations are done by the same model, the discrepancies in their results associates only with their parameters’ precision.

Figure 5.11 presents the PMSM output power which is calculated by employing various methods of d- and q-axis inductance determination. The armature resistance and flux linkage constant used in these calculations are provided by the manufacturer. The accuracy of the estimations using the presented methods is in agreement with the corresponding precision of the methods in determining the d- and q-axis inductances.

![Graph showing PMSM performance calculation](image)

Fig. 5.11. PMSM Performance calculation employing various methods of d- and q-axis inductances determination at 1,500 rpm.

The effect of the flux linkage inaccuracy on calculating the PMSM performance is illustrated in Fig. 5.12. The manufacturer d- and q-axis inductances and armature resistance are used in these calculations. Figure 5.13 studies the effect of the armature resistance accuracy on the performance calculations. The accuracy of the estimations using the presented methods confirms their precision in determining the armature resistance.
Table IV presents the root mean square error of the calculated output power with respect to the measurement for various methods of parameter determination. For calculating the parameter error, the manufacturer’s data are used as the reference and are considered to be accurate. Although the DC standstill tests do not provide the acceptable accu-
racy within the range of 10%, the calculated output power obtained from these methods has satisfactory accuracy. On the other hand, in spite of the relatively acceptable accuracy of the calculated flux linkage, the calculated output power which is obtained from the flux linkage calculation has significant discrepancy from measurement. In fact, the desired level of accuracy in parameter’s determination depends on the sensitivity of the performance prediction to the parameter variation.

### Table IV

**Sensitivity Analysis of the Output Power to the Equivalent Circuit Parameters**

<table>
<thead>
<tr>
<th>Method Employed</th>
<th>Parameter</th>
<th>Error in Parameter [%]</th>
<th>Error in Output Power [%]</th>
<th>Output power Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional DC test</td>
<td>$R_a$</td>
<td>6.73</td>
<td>3.66</td>
<td>0.396</td>
</tr>
<tr>
<td>Calculation</td>
<td>$R_a$</td>
<td>6.73</td>
<td>3.66</td>
<td></td>
</tr>
<tr>
<td>Modified DC test</td>
<td></td>
<td>0.93</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>DC standstill test (Using time constant)</td>
<td>$L_d/L_q$</td>
<td>23.81 / 21.43</td>
<td>9.39</td>
<td>0.657</td>
</tr>
<tr>
<td>DC standstill test (Flux measurement)</td>
<td>$L_d/L_q$</td>
<td>18.57 / 17.62</td>
<td>7.26</td>
<td></td>
</tr>
<tr>
<td>Calculation</td>
<td>$L_d/L_q$</td>
<td>10.95 / 8.57</td>
<td>4.97</td>
<td></td>
</tr>
<tr>
<td>On-load test ($L_q$ measurement)</td>
<td>$\lambda_f$</td>
<td>10.95 / 6.49</td>
<td>4.97</td>
<td></td>
</tr>
<tr>
<td>Open-circuit test</td>
<td>$\lambda_f$</td>
<td>0.00</td>
<td>3.41</td>
<td>4.97</td>
</tr>
<tr>
<td>Calculation</td>
<td>$\lambda_f$</td>
<td>8.09</td>
<td>39.79</td>
<td></td>
</tr>
</tbody>
</table>

A numerical expression of the sensitivity is presented in (47). According to this equation, the sensitivity of the performance factor, $\gamma$ to the parameter, $\rho$ is the ratio of the performance factor error to the parameter error. In this equation, $\gamma_{ex}$ is the measured performance factor, $\gamma_{cal}$ is the calculated performance factor, $\rho_{act}$ is the actual value of the parameter which is obtained from manufacturer’s data, and $\rho_{det}$ is the determined value of the parameter.

$$S_\rho^\gamma = \frac{\gamma_{ex} - \gamma_{cal}}{\rho_{act} - \rho_{det}} \frac{\rho_{act}}{\gamma_{ex}}$$ (47)

The sensitivity of the PMSM output power to the equivalent circuit parameters is presented in Table IV. The root mean square error of the output power is used in the sensitivity calculation. The parameter variation is 10% for all the calculations, and the sensitivity to d-axis inductance and q-axis inductance is assumed to be equal. According to Table IV, the sensitivity of the output power to flux linkage constant is more than its sen-
sitivity to d- and q-axis inductances and armature resistance. Therefore, more accurate methods need to be selected for flux linkage determination.

5.5 Novel d-q Axis Model of the PMSM

In this paper, two major factors in the inaccuracy of PMSM performance prediction are introduced; parameters’ error and modeling imprecision. Parametric sensitivity analysis of PMSM was conducted in previous section as an efficient approach to cope with the parameters’ inaccuracy. The second factor in the accuracy of PMSM performance prediction is modeling imprecision. In this section, a novel model for simulating the PMSM’s performance including the effect of saturation and core losses is proposed. The proposed model provides better accuracy in comparison with the conventional model. Application of this method, along with employing accurate equivalent parameters, results in the precise calculation of the PMSM performance.

The conventional d- and q-axis modeling of the PMSM is an effective method for the performance calculations of the PMSM when the effect of saturation and core losses are negligible. However, operating the machine at higher currents results in the saturation of the air gap magnetic flux, and high speed operations create higher eddy currents and core losses. In this section, a novel model for calculating the PMSM’s performance is developed. The proposed model includes the effect of the saturation and the core losses and provides more accuracy at higher speeds and larger currents in comparison with the conventional model.

The core loss in a PMSM is proportional to the square of the stator induced voltage \( E_i \). The PMSM core losses can be modeled by a resistor (core loss resistor) which is placed in parallel with the induced voltage. The phasor diagram of the under excited PMSM incorporating the core losses is illustrated in Fig. 5.14 (a) [79]. The steady-state d- and q axis model including the effect of core losses can be driven from the PMSM phasor diagram as illustrated in Fig. 5.14 (b). In a PMSM, the d- and q-axis currents are related to the internal voltage through (48).

\[
I_d = \frac{E_{iq} - E_f}{\omega_s L_{md}} - \frac{E_{id}}{R_c} ; \quad I_q = \frac{E_{id}}{R_c} + \frac{E_{id}}{\omega_s L_{mq}} \tag{48}
\]
The terminal voltage of the PMSM is related to the internal voltage and the terminal current through (49).

\[
\begin{align*}
V_d &= I_q \omega_s L_l - I_d R_a + E_{id} \\
V_q &= I_q R_a + I_d \omega_s L_l + E_{iq}
\end{align*}
\tag{49}
\]

Solving the set of equations in (48) for the d- and q- axis internal voltages and substituting it in (49), one can calculate the d- and q-axis voltages with respect to the d- and q- axis currents as described in (50).

\[
\begin{align*}
V_d &= I_q \omega_s \bar{L}_q - I_d \bar{R}_a - \alpha \varepsilon E_f \\
V_q &= I_q \bar{R}_a + \omega_s I_d \bar{L}_d + \varepsilon E_f
\end{align*}
\tag{50}
\]
Where \( \alpha \) is the ratio of the q-axis inductance to the core loss resistance and \( \varepsilon \) can be calculated by (51).

\[
\alpha = \frac{\omega_s L_{mq}}{R_c} ; \quad \varepsilon = \frac{R_c^2}{R_c^2 + \omega_s^2 L_{md} L_{mq}}
\]  

(51)

\( \bar{R}_a, \bar{L}_d, \) and \( \bar{L}_q \) are the equivalent parameters of the PMSM which incorporate the effect of core losses and are defined by the set of equations presented in (52).

\[
\begin{align*}
\bar{L}_d &= L_d + \varepsilon L_{md} \\
\bar{L}_q &= L_q + \varepsilon L_{mq} \\
\bar{R}_a &= R_a + \alpha \omega_s L_{md}
\end{align*}
\]  

(52)

Solving the set of equations in (11) for currents, the d- and q- axis currents can be determined by (53).

\[
\begin{align*}
I_q &= \frac{V_q \bar{R}_a + V_d \omega_s \bar{L}_d - E_f k_q}{\omega_s^2 \bar{L}_d \bar{L}_q + \bar{R}_a} \\
I_d &= \frac{V_q \omega_s \bar{L}_q - V_d \bar{R}_a - E_f k_d}{\omega_s^2 \bar{L}_q \bar{L}_q + \bar{R}_a^2}
\end{align*}
\]  

(53)

Where \( k_d \) and \( k_q \) are the coefficients of the excitation voltage in the current equations and can be calculated by (54).

\[
k_d = \varepsilon (\omega_s \bar{L}_{mq} + \alpha \bar{R}_a); \quad k_q = \varepsilon (\bar{R}_a - \alpha \omega_s L_{md})
\]  

(54)

To simplify the calculations, this paper proposes a novel d-q axis model of the PMSM which eliminates the parallel branch of the core loss resistance. Figure 5.15 illustrates the equivalent circuit of the proposed model. The d- and q axis excitation voltages displayed in this figure can be calculated by (55).

![Fig. 5.15. Novel d-q-axis model of the PMSM incorporating the core losses.](image-url)
The effect of saturation in the PMSM can be modeled by considering the d- and q-axis inductances as functions of the d- and q-axis currents. The d- and q-axis magnetizing inductances are related to d- and q-axis currents through the Fourier transform as expressed in (56) [80]. To include the effect of saturation and core losses simultaneously, the saturated d- and q-axis magnetizing inductances expressed in (56) should be applied to the equivalent parameters of the PMSM presented in (51), and (52).

\[
\begin{align*}
L_{mq} &= \sum_{n=0}^{N_e-1} a_{n-q} e^{-2\pi if_{n-q}} \\
L_{md} &= \sum_{n=0}^{N_e-1} a_{n-d} e^{-2\pi if_{n-d}}
\end{align*}
\]

(56)

In PMSM, the current in one axis contributes to saturation in the other axis due to the cross saturation effect. The cross saturation saliency is more significant when the d-axis current is positive [81]. In addition, injecting voltage carrier signal to the PMSM in rotor positioning applications results in high carrier currents and consequently increased cross saturation effects [82]. Since the d-axis current is not positive and the carrier current is zero in the investigations of this paper, the proposed model neglects the cross saturation effect.

5.5.1 Estimation of Core Loss Resistance

In order to use the proposed model in PMSM performance prediction, the magnitude of core loss resistance is required. In this section, a method for measuring iron loss resistance is presented.

The power flow in PMSM is presented in (57). In this equation, \( P_s \) is the sum of the output power, core loss and mechanical loss. According to (57), \( P_s \) has a linear relation with the square of internal voltage and \( R_c \) is the reciprocal of the slope of this linear function. Therefore, the core loss resistance can be obtained from the \( P_s - E_i^2 \) curve at constant torque and speed. Calculation of internal voltage using the terminal voltage and current is presented in (57) as well [34].

\[
E_d = \alpha \varepsilon E_f \quad ; \quad E_q = \varepsilon E_f
\]
\[
P_s = P_{in} - P_{cu} = P_{out} + \frac{E_i^2}{R_c} + P_{rot}
\]

\[
E_i = \sqrt{V_t^2 - 2R_aP_{in} + 3R_a^2I_t^2}
\]

Table V presents the estimated core loss resistance of the laboratory PMSM using the described method. According to this Table, core loss resistance of PMSM increases with the increase in speed. The relation of core loss resistance with speed is presented in (58) [83]. In this equation, \(R_{ce}\) is the PMSM eddy-current loss resistance, and \(R_{ch}\) is the hysteresis loss resistance.

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Core loss resistance (Ω)</th>
<th>Eddy-current loss resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>35</td>
<td>52.08</td>
</tr>
<tr>
<td>500</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>44</td>
<td>Hysteresis loss resistance (Ω)</td>
</tr>
<tr>
<td>1,100</td>
<td>46.8</td>
<td>4.62</td>
</tr>
<tr>
<td>1,300</td>
<td>46.4</td>
<td></td>
</tr>
<tr>
<td>1,500</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{1}{R_c} = \frac{1}{R_{ce}} + \frac{1}{R_{ch} \times f}
\] (58)

5.5.2 Verification of the Model Accuracy through Experimentation

In this section, the accuracy of the proposed model is compared with the conventional model through experimentation. Figure 5.16 illustrates the output power of the laboratory PMSM at 1500 rpm, calculated by the proposed model and the conventional dq-axis model. The armature resistance and the flux linkage used in the calculations are obtained from manufacturer data. The saturation characteristics of the PMSM presented in Fig. 5.9 (a) and (b) are used for modeling the saturation of the d- and q-axis inductances. The core loss resistance of the PMSM is obtained from Table V. Since the calculations are done by the same set of parameters for both models, the discrepancies in their results associate
only with the model accuracy. Comparison of the calculated results with the measurements validates the higher accuracy of the proposed model. As illustrated in Fig. 5.16, the inaccuracy of the conventional model increases at higher currents due to the increased effect of the saturation.

Table V presents the root mean square error of the calculated output power with respect to the measurement for both the conventional model and the proposed model at different speeds. According to this table, at low speeds, the core loss is relatively small and neglecting it in the conventional model doesn’t produce significant error in comparison with the new model. However, as the speed increases, the effect of core loss on the PMSM performance increases. Therefore, at high speeds, neglecting core loss in the conventional model produces noticeable error compared to the new model and the experimental results.

Table VI compares the accuracy of the conventional model and the proposed model at 1,500 rpm for different currents. According to this table, the accuracy of the proposed model is almost constant for different currents; whereas, in the conventional model, the calculation error increases as the current increases.
### Table VI

**Root Mean Square Error of the Output Power at Different Speeds**

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Error (%), conventional model</th>
<th>Error (%), proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>4.48</td>
<td>4.13</td>
</tr>
<tr>
<td>500</td>
<td>6.60</td>
<td>4.29</td>
</tr>
<tr>
<td>700</td>
<td>6.10</td>
<td>3.21</td>
</tr>
<tr>
<td>900</td>
<td>6.76</td>
<td>3.18</td>
</tr>
<tr>
<td>1100</td>
<td>6.97</td>
<td>2.96</td>
</tr>
<tr>
<td>1300</td>
<td>7.25</td>
<td>3.14</td>
</tr>
<tr>
<td>1500</td>
<td>7.35</td>
<td>3.11</td>
</tr>
</tbody>
</table>

### Table VII

**Root Mean Square Error of the Output Power at Different Current**

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>% Error, Conventional model</th>
<th>% Error, Proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.7</td>
<td>11.11</td>
<td>3.02</td>
</tr>
<tr>
<td>28.2</td>
<td>8.85</td>
<td>3.04</td>
</tr>
<tr>
<td>15.7</td>
<td>6.10</td>
<td>2.84</td>
</tr>
<tr>
<td>10.9</td>
<td>4.29</td>
<td>3.32</td>
</tr>
<tr>
<td>8.30</td>
<td>3.62</td>
<td>3.30</td>
</tr>
</tbody>
</table>
6 CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In this thesis, the potentials for electrified vehicles to penetrate the transportation market were studied. According to the statistics, it is predicted that 25% of car market will be electrified by 2020. In this regard, the additional load demand for EV battery charging at 25% EV penetration was estimated. Considering the impact of EV charging on the harmonics of the grid, loss and thermal modeling of distribution transformers incorporating the grid harmonics were presented. Moreover, the impacts of additional EV load demand on load loss, temperature and aging acceleration factor of a sample 100 kVA distribution transformer was calculated. Calculation results demonstrate that the existing power system is unable to accommodate the additional EV load demand as the aging acceleration factor of DTs exceeds its critical value during the charging hours. For the investigated transformer, the other stray losses are more affected by the EV penetration than eddy current loss. Moreover, the effect of EV penetration on top-oil temperature is more than hottest-spot conductor temperature and the rise in the hottest spot temperature is mainly caused by the rise in the top-oil temperature.

Loss and thermal analysis of the investigated transformer at various EV penetrations were performed as well. Calculation results indicate that in order to guarantee safe opera-
tion of DTs, EV penetration should not exceed 20%. For EV penetrations higher than this value, two affective approaches were proposed to regulate the charging load demand and reduce its negative impacts on transformers.

Optimization of charging schedule for EVs was investigated in this thesis. In order to minimize the negative impacts of EV battery charging on distribution transformers, the charging schedule was formulated as an optimization problem. Newton Method and also Karush-Kuhn-Tucker (KKT) conditions were investigated as effective optimization algorithm for solving the developed optimization problem. Using Newton method for solving the optimization problem and MATLAB software for performing the corresponding computations, a novel load management program for EVs was developed.

The effectiveness of the proposed charging schedule was validated through a comparative study. In this regard, the impacts of EV charging on a sample 100 kVA distribution transformer for both smart EV charging and uncontrolled off-peak charging were investigated. Calculation results demonstrated that application of the optimal charging schedule reduces the load loss, hottest-spot temperature and lifetime of the sample distribution transformer significantly. According to calculations, the proposed charging schedule maintains the safe operation of transformers for EV penetrations smaller than 80%; whereas, EV penetration is limited to 20% when uncontrolled off-peak charging is used. In fact, with the proposed charging schedule, the existing power system will have the capacity to provide the load demand for up to 109.7 electric vehicles without threatening the lifetime of DTs.

Moreover, a new design for smart automotive systems is proposed which minimizes the users’ electricity payment and waiting time. The developed smart system is suitable for electric vehicles and considers the charging profile of EV batteries.

The negative impacts of EV penetration on DTs can be reduced by increasing the efficiency of EV powertrain. Since PMSM is one of the most efficient electric motors, its application in EVs contributes to increase in EVs’ efficiency. In order to maximize the efficiency of PMSM, control of PMSMs based on their efficiency maps was introduced. Considering the significance of accurate modeling in the control of PMSM, this thesis focused on accurate modeling of PMSM and the sources of error in PMSM steady-state performance estimation.
In this regard, a detailed analysis and a comparative study of the various methods for determining the PMSM parameters and characteristics were conducted. Several methods for determining the parameters which are available in literature along with novel methods developed by the authors were proposed. The presented models were applied to a laboratory PMSM and its equivalent circuit parameters were determined with varying level of accuracy. The resultant parameters were employed for the performance calculation of the PMSM. The effect of the parameter inaccuracy on the performance estimations was examined through experimentation. A discrete sensitivity coefficient was proposed and the parametric sensitivity analysis of the PMSM was performed. According to the experimental results, the PMSM’s output power is highly sensitive to the flux linkage constant, while its sensitivity to d- and q-axis inductances and armature resistance is moderately low. A comprehensive study on the desired accuracy of the performance calculations, the performance sensitivity to the parameters, and the complexity of the parameter determination methods leads to an effective selection of the appropriate method for parameter determination. Once the parameters are determined, the performance calculation can be improved by enhancing the PMSM’s model accuracy. In this paper, a novel dq-axis model of the PMSM including the core losses and saturation saliency was proposed. The proposed model was applied to the laboratory PMSM and its higher accuracy in comparison with the conventional d- and q-axis model was validated.

6.2 Future Works

The investigations presented in this thesis introduce several lines of research which should be pursued. In addition to minimization of negative impacts on DTs, optimization of power system losses, and voltage regulation is also desired for power system stability and reliability. Therefore, it is beneficiary to incorporate these factors in optimization of EVs’ charging schedule as well. In future research, an optimal charging schedule based on optimization of negative impacts on DTs, power system losses, and voltage regulation will be developed.

In chapter 3, a novel smart system suitable for electric vehicles was presented. Future research will thoroughly investigate the implementation of the proposed smart system.
Quadratic programming will be used for solving the developed optimization problem and the effectiveness of the developed smart system will be validated through calculations.

Regarding application of PMSM in electric vehicles, the proposed PMSM model presented in chapter 4 will be used for developing a suitable controller which operates based on the PMSM efficiency map and maximizes its efficiency. Contribution of the proposed controller to reduction of EV daily load demand will be evaluated based on calculation results.


[23] H. Feng, Y. Li, Z. Huang, and L. Su, "A direct torque control (DTC) system's startup modeling and simulation of Permanent Magnet Synchronous Motor (PMSM) on electric vehicle (EV)," in Proc. of Electrical and Control Engineering Conference (ICECE), Sept. 2011.


Vita Auctoris

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