# OPTIMIZE PERFORMANCE OF ELECTRIC DRIVE FOR ELECTRIC VEHICLE

**Ph.D. Synopsis**

Submitted to Gujarat Technological University

in

**Electrical Engineering**

by

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## 1. Title of the thesis:

Optimize Performance of Electric Drive for Electric Vehicle

## 2. Abstract:

Depletion of fossil fuels, growing climate change due to global warming, air pollution produced by the vehicles, urbanization, and pollution in big cities are raising public awareness for more sustainable mobility, meaning efficient energy usage and low (or zero) local emissions are the critical issues in the present scenario. Moreover, the growing number of vehicles on our roads each year is forcing industry players and policy-makers to explore alternative forms of mobility with a smaller $CO_2$ footprint to reduce the dependency on fossil fuels.

All these issues have paved a way to increase the use of electric vehicles and hybrid electric vehicles. The attractions of electric vehicles (EVs) are mainly due to their advantages like higher energy efficiency of the drive train, deficient noise levels, and zero tailpipe emissions when powered solely by the battery.

For EVs to be genuinely viable, the significant need is to overcome various challenges. The considerable difficulties are the high initial cost of the battery and the lower driving range. The main objective of this research is to investigate the performance of the electrical drive of Electric Vehicle by the use of optimization of control parameters by different control methods and to propose the control method to provide a better solution.

Online control of optimization with variable speed and torque of Electric Vehicle is highly nonlinear. The algorithm used to solve this optimization problem is expected to satisfy the objective every time the driver changes the speed and torque control commands and must also be prompt. However, in the majority of literature, it is proposed using look-up tables or with the optimization algorithms, which takes a long time to converge. The proposed algorithm developed here is used to overcome the above drawbacks.

The study concluded with a recommendation to use the proposed algorithm to obtain the optimized performance of Electric Drive for Electric Vehicle. The experimental prototype is developed to verify the results.

## 3. Brief description of the State of the Art of the Research Topic:

The electric vehicles are of two types, 1) Only battery operated electric vehicles, and 2) hybrid electric vehicles. The only battery operated electric vehicles consist of only electrical equipment, and its driving range is limited. The power electronic system and control technique should be efficient to improve the efficiency of electric vehicles, especially in case of only battery operated Electric Vehicles. The selection of a power semiconductor device, converters, and its control techniques and switching strategies are essential for better performance.

Different types of electrical machines have been proposed and investigated for Electric Vehicles, like Permanent magnet motors [1-4], Induction motor[5,6], Switched Reluctance Motor[7], Comparison of the different motor based on performance, efficiency and vibration [8,9]. Interior Permanent Magnet Synchronous Motor (IPMSM) offers highest average torque, higher efficiency, reduced inverter size, better starting torque and dynamic response, high no-load magnetic field with no current excitation (no rotor copper losses), reduced the size and weight of EV. Thus this thesis investigates the candidature for IPMSM for Electric Vehicles.

For Electric Vehicles, the primary concern is the limited driving range due to a limited battery source. Thus it is highly recommended to reduce the losses of the electric drive system used in Electric Vehicles. This thesis considered the application of Interior Permanent Magnet Synchronous Motor for Electric Vehicles. Different optimization control strategies are proposed in the literature to optimize the performance of IPMSM drive and reduce the losses of the electric drive system. The field-oriented control method is proposed in [10], with zero direct-axes current component (i.e., $i_d$=0) and optimized direct axis current control. As the direct axis-current component is kept zero, this method does not use the reluctance torque of IPMSM, and so the torque control is not optimal. Unity Power Factor Control proposed in [11] produces reluctance torque but does not focus on the losses. But unity power factor control cannot achieve maximum efficiency under each operating condition**.** Maximum Torque per Ampere (MTPA) Control investigated in [12] optimizes only copper losses. Maximum Efficiency per Ampere Control utilized in [13], focuses on copper loss and iron loss of the motor. Loss model based Loss Minimization Control proposed in [14] accounts the copper loss and iron loss both. The authors of [15] utilized search based loss minimization Control, but they converge time to the optimum point is more. The performance of search based loss minimization does not suffer from machine variables change but offers higher current and voltage harmonics [15] and high torque ripple[15].

Even many researchers have investigated overall efficiency improvement of the IPMSM drive; the investigation of these methods for Electric Vehicles is missing in the literature. The main aim of the work proposed in this thesis is to determine the best suitable control method for Interior Permanent Magnet Synchronous Motor drive for Electric Vehicles. This thesis compares the results obtained from three different control methods 1) Field Oriented Control (FOC) 2) Direct torque control with space vector modulation (DTC-SVM). 3) Direct Reactive Energy and Torque Control [16]. The Simulation results of these three methods are obtained without and with optimization of losses.

Neural network have been used for maximum efficiency control of induction motor[17-18]. The authors [19] developed ANN-based control but demonstrated the results for MTPA and flux weakening control only. The author of [20] proposed adaptive neural network, but it is for open loop.

The online control of optimization for Electric vehicles is missing in the literature. The results of this thesis contribute to the selection of the online control method for Electric Vehicle. System performance is checked without and with loss minimization control algorithm for optimization of losses of IPMSM with online control. Simulations are prepared for the parameters of the motor as rated power of 5HP, rated input voltage 183Volt, rated speed 183 rad/sec and rated torque 19.1 N-m [21].

# 4. Motivation and Definition of the Problem:

Investigations have shown that inconceivable catastrophic changes in the environment will take place if the global temperatures increase by more than 2° C (3.6° F). A warming of 2° C (3.6° F) corresponds to a carbon dioxide ($CO_2$) concentration of about 450 ppm (parts per million) in the atmosphere. Automobiles are the major contributors to the $CO_2$ emission. Therefore, there is now widespread acceptance of the need to tackle climate change. Vehicles are the major contributors to the $CO_2$ emission. Thus electrification of transport by electric vehicles, hybrid electric vehicles, or plug-in hybrid electric vehicles is accepted as one of the realistic solutions to meet the greenhouse gas reduction. Also, there is a need for alternate energy vehicles due to limited fossil fuels.

Following are the advantages of all Electric Vehicles compared to Internal Combustion Engine based Vehicles:

1. Electric vehicles convert about 59–62% of the electrical energy from the grid to mechanical power at the wheels—conventional gasoline vehicles only convert about 17–21% of the energy stored in gasoline to power at the wheels[22].
2. Environmentally friendly. EVs emit no tailpipe pollutants, although the power plant producing the electricity may emit them. Electricity from nuclear, hydro, solar, or wind-powered plants causes no air pollutants.
3. Performance benefits. Electric motors provide quiet, smooth operation and stronger acceleration and require less maintenance than ICEs.
4. Reduce energy dependence. Electricity is a domestic energy source.

EVs do, however, face significant battery-related challenges:

1. A limited driving range of most EVs, require frequent recharging. Gasoline vehicles can go over 300 miles before refueling.
2. Recharge time: Fully restoring of the battery pack can take 4 to 8 hours. Even a "quick charge" to 80% capacity can take 30 min.
3. Battery cost: The large battery packs are expensive and may need to replace one or more times.
4. Bulk & weight: Battery packs are bulky and take up considerable vehicle space.

Researchers are working to develop solutions to overcome the above challenges. The different methodology includes improvement in battery technology, improvement in motor technology, and advancement in motor control technology.

Researchers have investigated the use of different types of motors for electric vehicles. Among all of them, Permanent magnet synchronous motor (PMSM) is a better choice considering the high efficiency it offers. Different control strategies have been proposed for PMSM based EV. All these control strategies do not emphasize on the efficiency of the drive system, which is essential for Electric Vehicles. Also, PMSM for Electric Vehicles is designed with low inductance winding to offer a wide speed-torque range with limited battery voltage, which is responsible for the higher harmonic iron loss. The overall system considering the all possible losses and its online optimization is unexplored in the literature.

**Thus the main aim of this thesis is to develop an overall system of Electric Vehicle with Interior Permanent Magnet Synchronous Motor, which works most efficiently with the limited energy source available. For this purpose, this thesis analyzed different control strategies with loss minimization techniques and proposed the novel and most suitable method which operates online and minimizes the overall system losses and improves the system performance. Also offers better efficiency under different driving conditions.**

# 5. Objective and Scope of work:

- Sizing and designing of Electrical Drive system of an electric vehicle based on vehicle dynamics.
- To investigate control strategies to optimize the energy efficiency of Electric Drive System.
- To analyze the losses of the system with and without optimization.
- To propose the algorithm for losses reduction, as reduced losses of the system improve the efficiency of the system, improves the battery life, reduces the thermal stress on various components and intern enhances the reliability of the overall system.
- The design is to be validated using the simulation for optimized control of Interior Permanent Magnet Synchronous Motor(IPMSM) drive based Electric Vehicle.
- To develop a controller for IPMSM that provides online optimization.
- To develop the experimental prototype to support the results.

# 6. Original Contribution by the Thesis.

The main contributions in the thesis are:

1) Sizing and designing of the propulsion system of an electric vehicle have been done by using the vehicle dynamics and rated values of power, torque, and speed of the motor are calculated based on the selected Electric Vehicle ratings.
2) The dynamic equivalent circuit of IPMSM is modeled considering the effect of core losses. The developed IPMSM model is prepared in the simulation for analysis and is being used to create the overall drive for the Electric Vehicle.
3) This thesis work has analyzed three control strategies for electrical drives for IPMSM to determine suitability for Electric Vehicles. Control strategies analyzed using MATLAB software simulations are: 1) Field oriented control 2) Direct torque control 3) Direct

reactive power and torque control. All these control strategies are analyzed with and without optimization of losses.

4) Developed the overall system for Space vector modulated Field oriented controlled Interior Permanent Magnet Synchronous Motor (IPMSM) drive based Electric Vehicle.
5) This thesis proposes an online optimization algorithm for the Electric Vehicle with minimum losses under different driving conditions.
6) The designed system is validated using MATLAB software simulation and hardware implementation.

# 7. Methodology of Research, Results / Comparisons

Following control techniques for Interior Permanent Magnet Synchronous Motor Drive are simulated using MATLAB Simulink software. With and without optimization results for these control strategies are analyzed to determine the suitability for the Electric Vehicles.

1) Space Vector Modulated Field Oriented control of IPMSM drive with direct-axis current control.
2) Space Vector Modulated Direct torque controlled IPMSM drive.
3) Direct reactive energy and torque controlled IPMSM drive.

For the Electric vehicle application, the main aim is to achieve better efficiency and minimum losses of the overall system. Following are the results obtained from the simulation of the above-listed methods:

## 7.1 Control strategies for optimization of losses of IPMSM drive for Electric Vehicles.

### 7.1.1 Direct axis current control for Field Oriented Control-Space Vector Modulation for IPMSM Drive without Optimization and with Optimization[21]

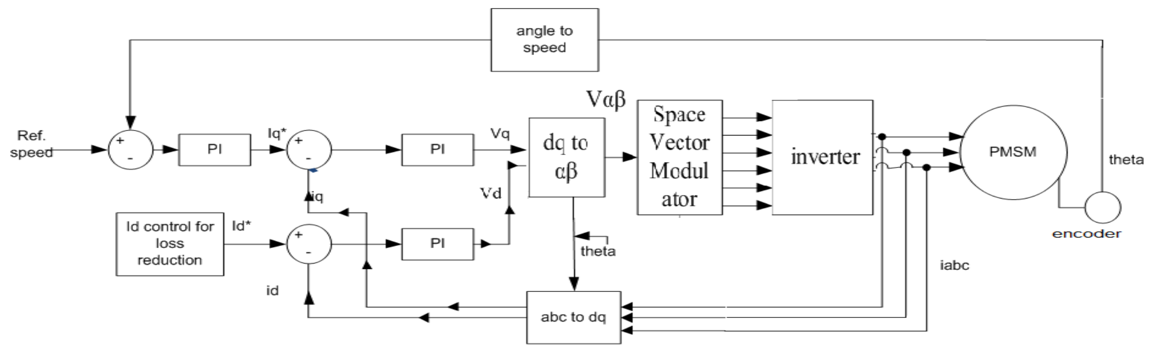


Fig.1. Field Oriented Controlled IPMSM drive for Electric Vehicle with d-axis current control.

In field oriented control technique, d-axis and q-axis components are parts of the stator current. Here, d-axis current controls the flux while the q-axis current controls the torque in the machine.

Figure 1 shows the field oriented controlled IPMSM drive system. The d-axis and q-axis current control loop generate the reference voltages $V_d$ and $V_q$, which are used to generate gate pulses for the inverter using space vector modulation. The system performance is analyzed for two cases: Case 1: The referenced d-axis current ($i_d$*) = 0 and Case 2: The referenced d-axis current ($i_d$*) = Optimized value obtained from loss minimization algorithm.

### 7.1.2 Direct torque control with space vector modulation (DTC-SVM) without optimization and with optimization of losses by controlling the flux in the IPMSM.[26]

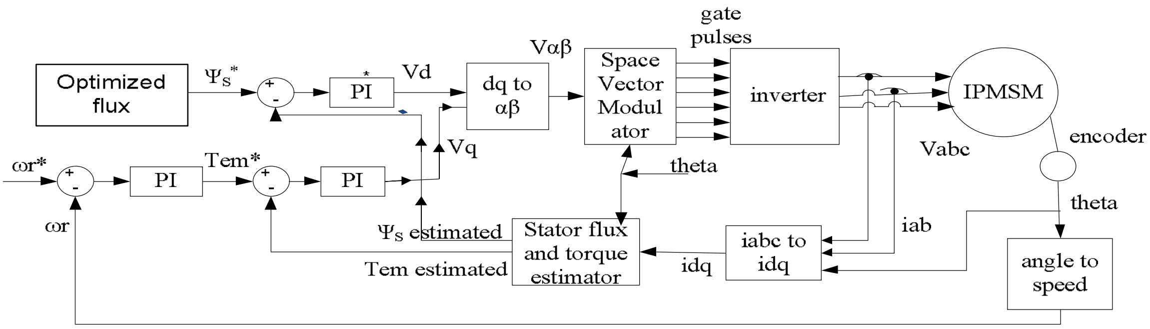


Fig. 2. DTC-SVM with optimization of losses for IPMSM drive

Another control method investigated is DTC-SVM with optimization of losses for IPMSM drive. As shown in figure 2, the measured current signals from motor terminals are converted to d-axis and q-axis components in the rotor reference frame (i.e., $i_d$ and $i_q$). Estimator block estimates the actual values of flux and electromagnetic torque from the current id and $i_q$. The flux and torque control loops generate the reference voltage vectors $V_d$ and $V_q$ for d-axis and q-axis voltage, which are used to generate gate pulses for inverter using space vector modulation. The system performance is analyzed for two cases: Case 1: The reference flux as per the rating of the machine and Case 2: The optimized reference flux obtained from loss minimization algorithm.

### 7.1.3 Space Vector Modulated Direct Reactive Power and Torque Control (DRPTC-SVM) of IPMSM without Optimization [16] and with Optimization.

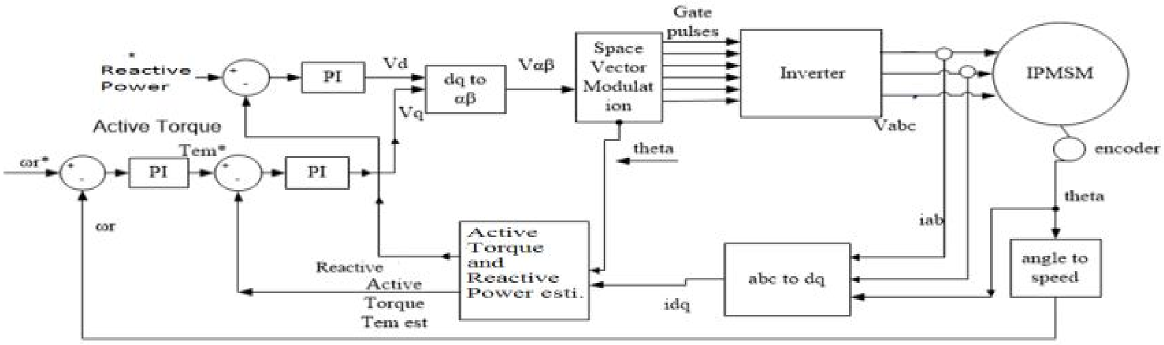


Fig. 3. Block diagram for Space Vector Modulated Direct Reactive Power and Torque Control (DRPTC-SVM) of IPMSM

This method is based on the instantaneous reactive power theory. Unlike, DTC-SVM, this method controls the reactive power and torque. The author of [16] has not analyzed the system for optimization.

### 7.2 Results and Discussion for different control strategies for IPMSM drive:

#### a) Results of Optimized direct-axis current control for Field Oriented Control-Space Vector Modulation (FOC-SVM) based IPMSM Drive for 50% rated torque and rated speed.

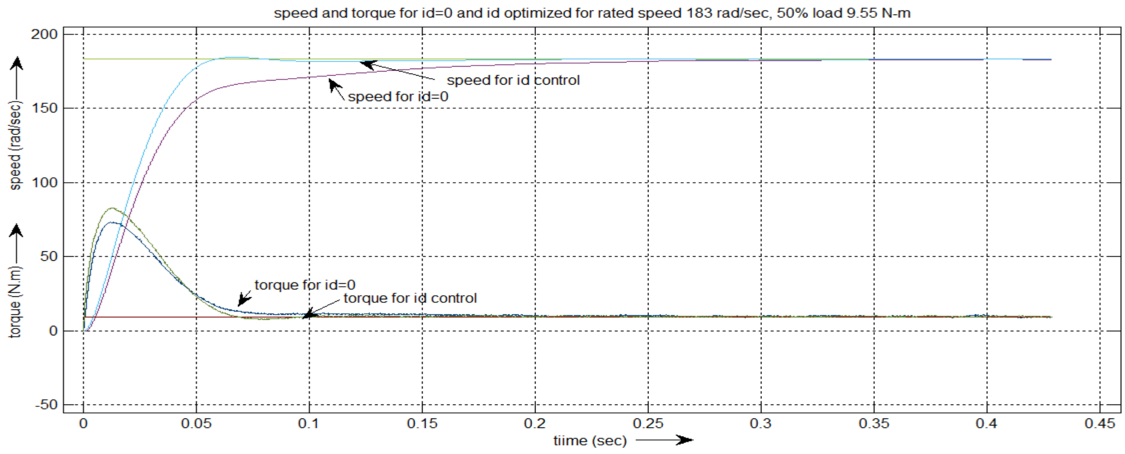


Fig. 4. Speed and Torque results of FOC-SVM based IPMSM drive without optimization and with optimization

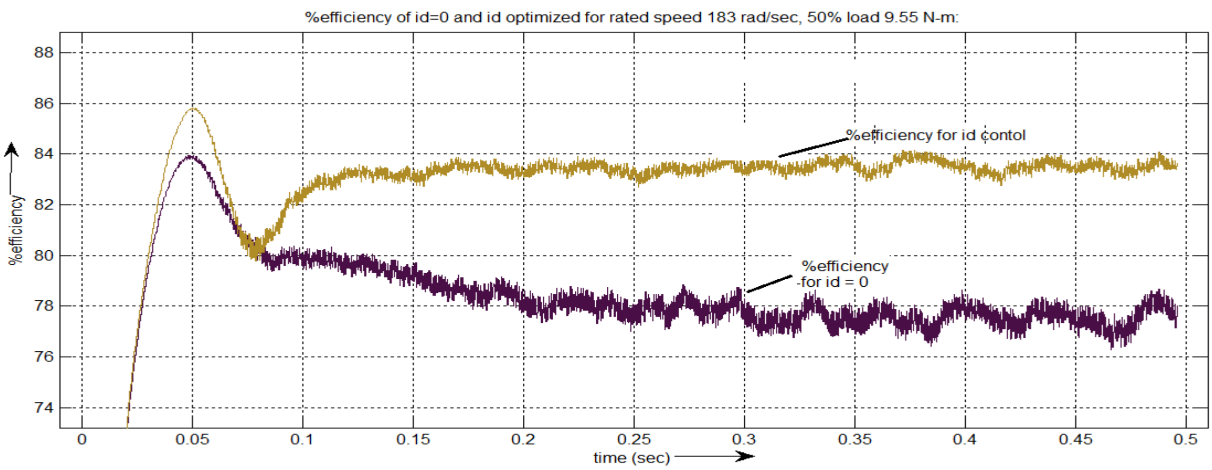


Fig. 5. Efficiency results of FOC-SVM based IPMSM drive without optimization and with optimization

Table 1. Summery of results at different load torque:

| Sr. No. | loading | Load torque (N-m) | Speed (rad/sec) | “id” Optimizated or not | id (amp) | Iq (amp) | Ipeak (amp) | Wcu – copper loss (watt) | Wfe- iron loss (watt) | Mech. Loss (watt) | Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100% | 19.1 | 183 | no | 0 | 25.01 | 25 | 227 | 533.7 | 14.2 | 82.49 |
| 2 | 100% | 19.1 | 183 | yes | -17.16 | 20.62 | 27 | 262.2 | 259.7 | 14.2 | 86.85 |
| 3 | 75% | 14.325 | 183 | no | 0 | 19.56 | 19.56 | 138.9 | 470.6 | 14.2 | 80.79 |
| 4 | 75% | 14.325 | 183 | yes | -16.46 | 16.29 | 23.5 | 194.8 | 226.5 | 14.2 | 85.71 |
| 5 | 50% | 9.55 | 183 | no | 0 | 15.05 | 15.5 | 82.21 | 431.9 | 14.2 | 77 |
| 6 | 50% | 9.55 | 183 | yes | -15.97 | 12.98 | 20.5 | 153.8 | 207.5 | 14.2 | 83.55 |
| 7 | 25% | 4.775 | 183 | no | 0 | 10 | 10 | 43.28 | 403.8 | 14.2 | 68.02 |
| 8 | 25% | 4.775 | 183 | yes | -15.65 | 8.233 | 17.5 | 113.7 | 184.8 | 14.2 | 74.32 |

**b) Results of Direct torque control with space vector modulation (DTC-SVM) with optimization of losses by controlling the flux in the IPMSM for rated torque and rated speed.**

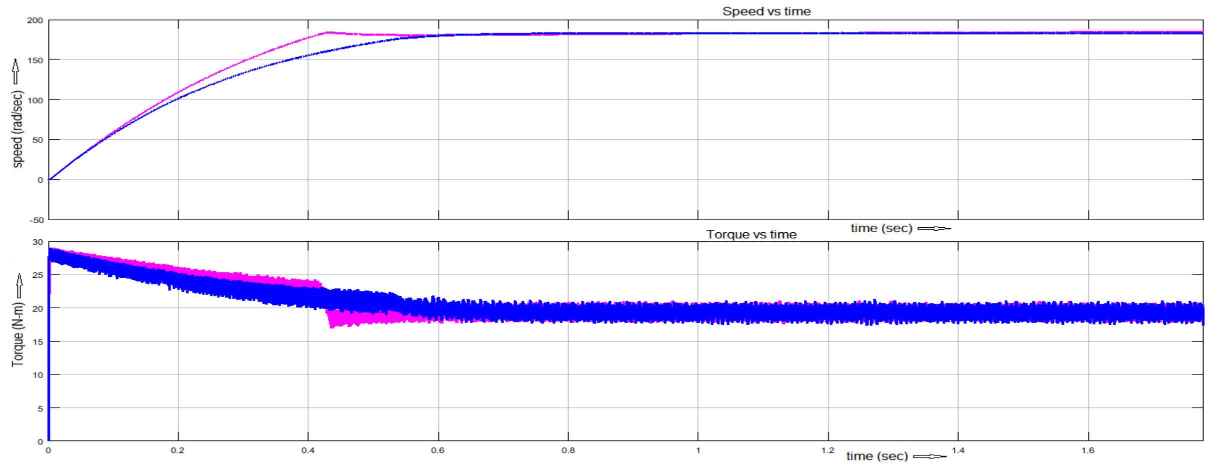


Fig. 6. Speed and torque results of DTC-SVM based IPMSM drive without optimization and with optimization

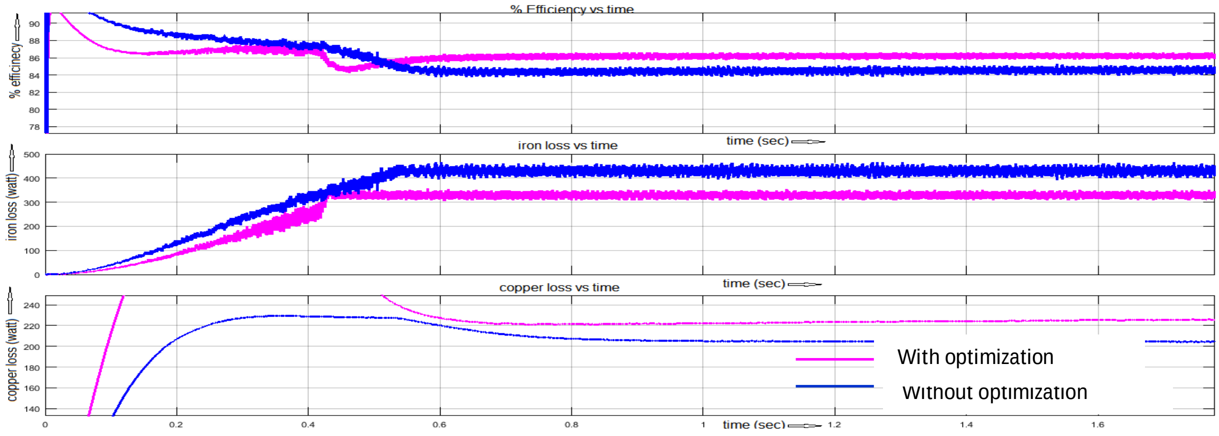


Fig. 7. Efficiency, iron loss, and copper loss results of DTC-SVM based IPMSM drive without and with optimization

### c) Results of Space Vector Modulated Direct Reactive Power and Torque Control (DRPTC-SVM) of IPMSM for 50% rated speed and 50% rated torque:

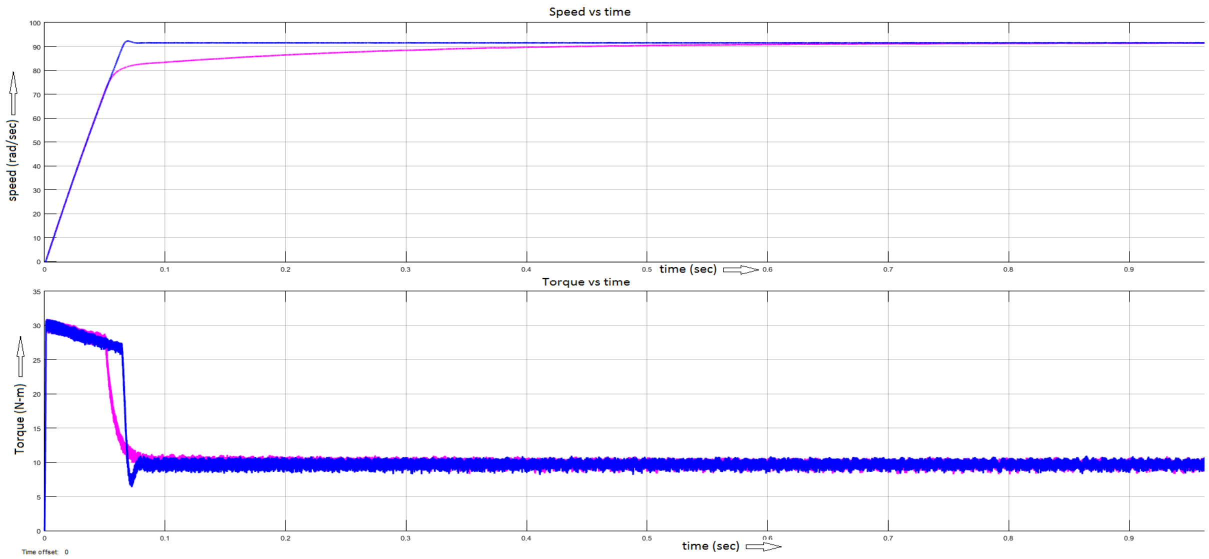


Fig. 8. Speed and torque results of DRPTC-SVM based IPMSM drive without optimization and with optimization

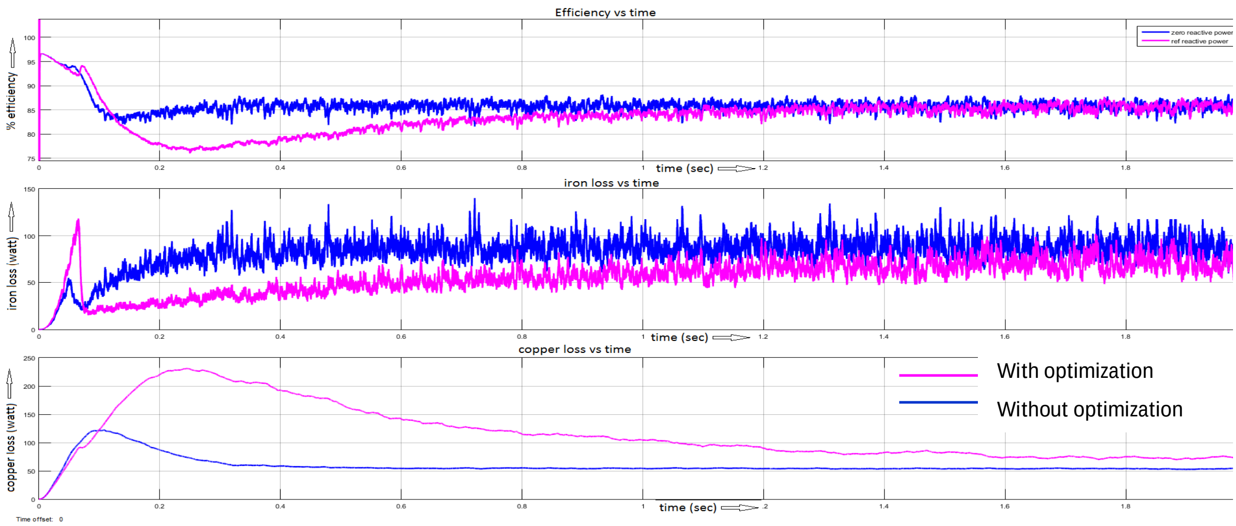


Fig.9. Efficiency, iron loss and copper loss results of DRPTC-SVM based IPMSM drive without with optimization

Table 2. Efficiency results without optimization and with optimization for FOC-SVM, DTC-SVM, and DRETC-SVM control strategies for IPMSM for Electric Vehicles application.

| Sr. No. | Load Torque in % | Speed (rad/sec) | Control Strategy | Efficiency (%) without optimization | Efficiency (%) with optimization |
|---|---|---|---|---|---|
| 1 | 100% | 100% | FOC-SVM | 82.49 | 86.85 |
| 2 | 100% | 100% | DTC-SVM | 84 | 86 |
| 3 | 100% | 100% | DRPTC-SVM | 87 | 87 |
| 4 | 50% | 50% | FOC-SVM | 84.54 | 85.73 |
| 5 | 50% | 50% | DTC-SVM | 85 | 85 |
| 6 | 50% | 50% | DRPTC-SVM | 85 | 85 |

Figure 4 to figure 9 shows the results for speed, torque, efficiency, copper loss, and iron loss for three different control methods of FOC-SVM, DTC-SVM, and DRPTC-SVM without optimization and with optimization. Tables 1 and 2, show the numerical values for the comparison for without optimization and with optimization for different speed and torque.

The FOC-SVM based IPMSM drive offers better efficiency, better response time, and reduced torque pulsation compared to the other two control strategies.

Thus further results of online control of optimization of Electric Drive for Electric Vehicle are developed for FOC-SVM based IPMSM drive.

## 7.3 Online Optimized Performance of Electric Drive for Electric Vehicle:

### 7.3.1 Overall system block diagram for Electric Vehicle

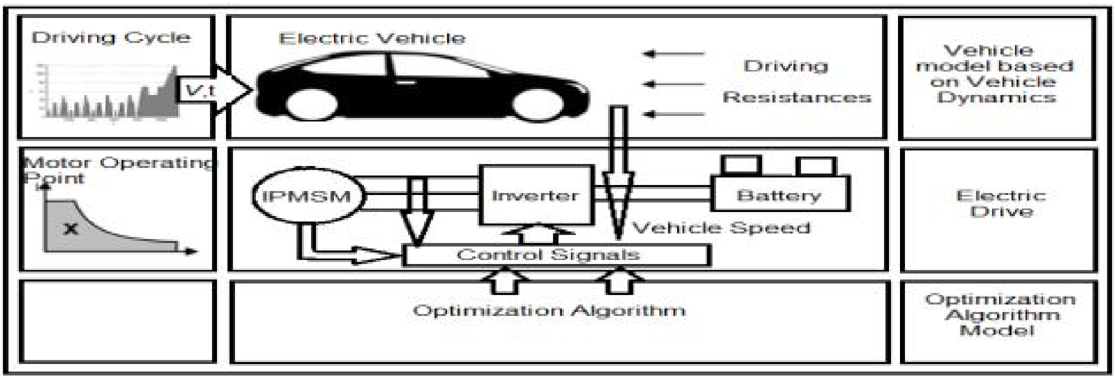


Fig. 10. Overall System Block Diagram for Electric Vehicle

Figure 10 shows the overall proposed block diagram of Electric Vehicle(EV). The Electric Vehicle consists of IPMSM drive. Li-ion battery technology is selected as energy source for considered EV as it posses high specific power, high specific energy, and long life requirement for battery of Electric Vehicle[23].

This research proposes the use of Particle Swarm Optimization (PSO) based Artificial Neural Network (ANN) for online control of Electrical Drive for Electric Vehicle. Particle Swarm Optimization based ANN is proposed in [24,25] for predicting pollutant levels. The results prove that it has better training performance, faster convergence rate, as well as a better predicting ability than Back Propagation based ANN. PSO is used for weight training of multi-layer feed forward neural network. In PSO, real number strings are adopted to code all the particles.Each real number coded string stands for a set of weights, which make up of one ANN together with all its nodes. Here, each bit of a particle is a real number that stands for a linking weight of the given ANN.

The Particle Swarm Optimized Artificial Neural Network using the loss minimization optimization is used to propose the online optimization of losses. The Electric Vehicle performance is analyzed under driving cycle and performance improvement is checked for the proposed online optimization.

### 7.3.2 Result of Electric Vehicle performance with and without optimization with loss minimization algorithm based on PSO optimized ANN control:

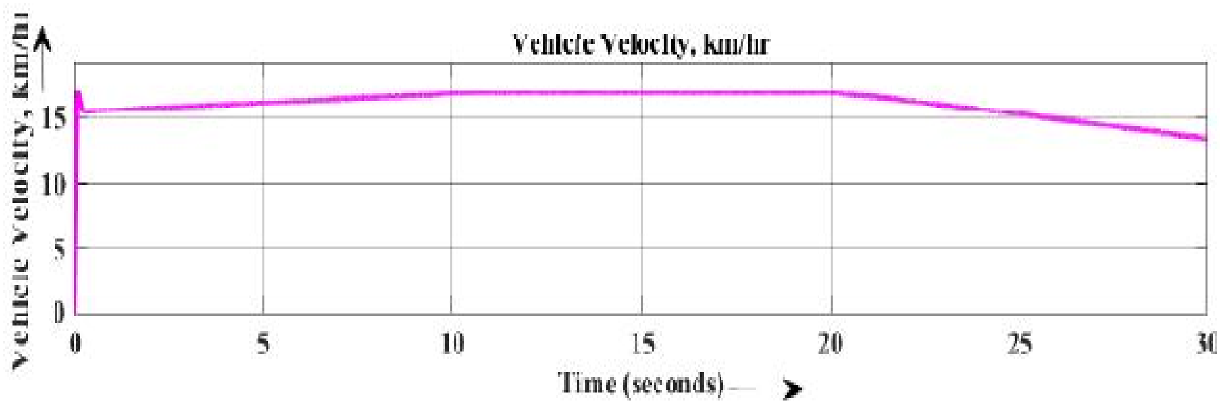


Fig. 11. Vehicle Velocity in km/hr

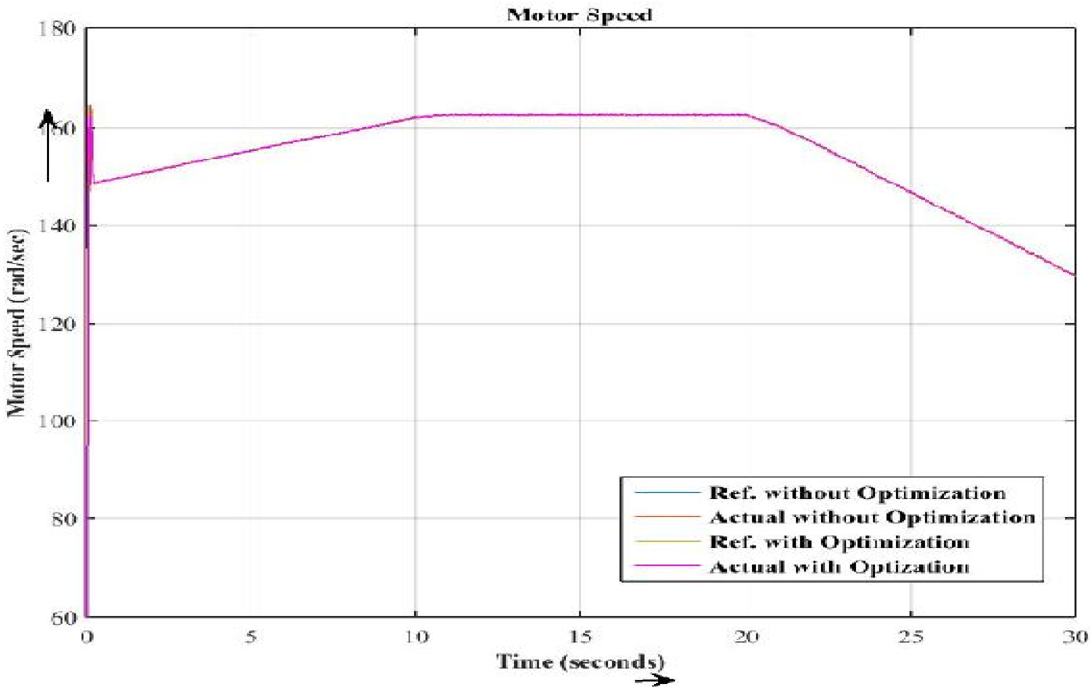


Fig. 12. Motor Speed in Rad/sec

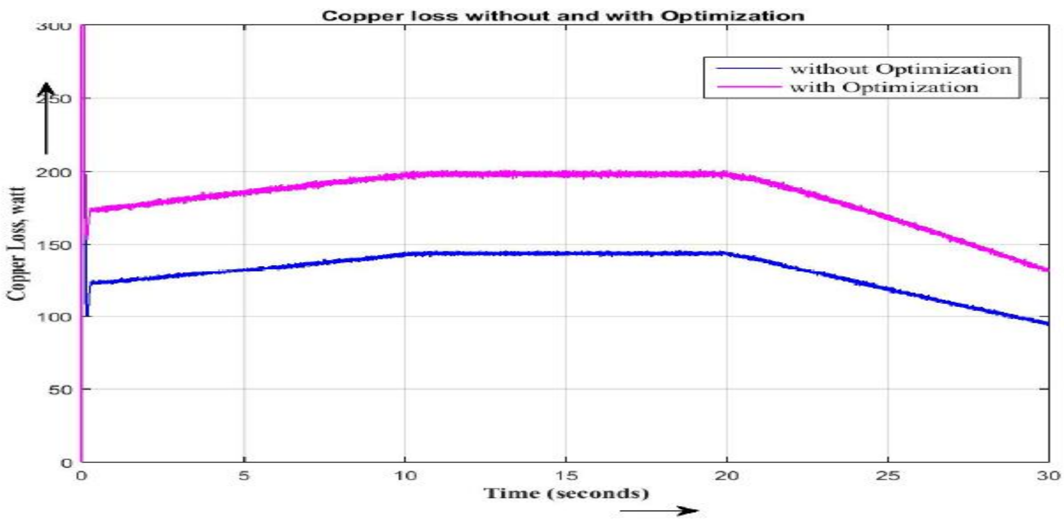


Fig. 13. Copper Loss without and with Optimization

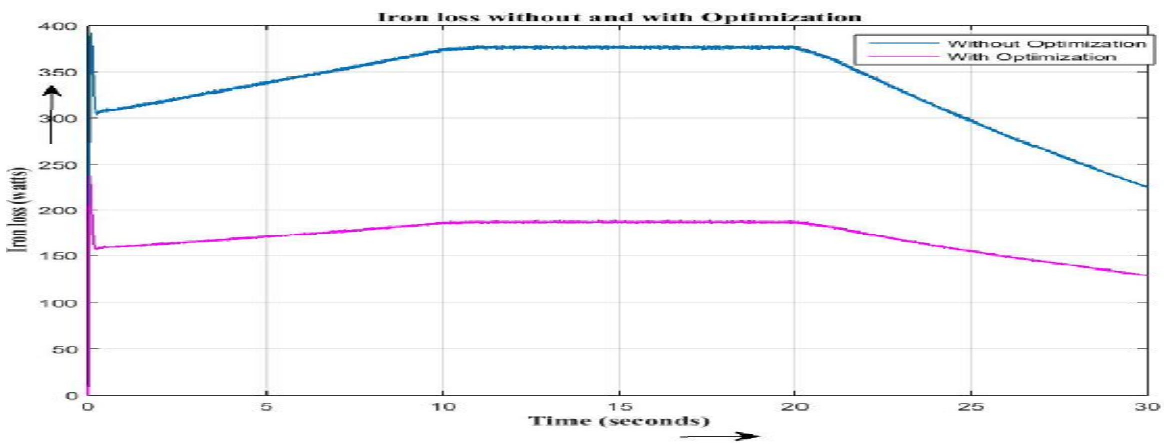


Fig. 14. Iron loss without and with Optimization

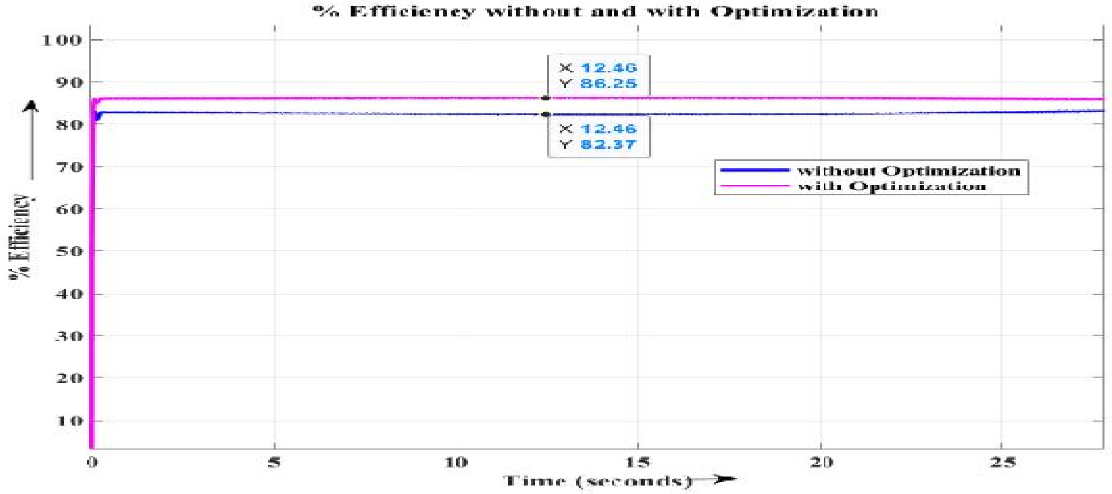


Fig. 15. % Efficiency without and with Optimization

Figure 11 to 15 shows the performance parameters of designed Electric Vehicle. Figure 15 proves the increase in efficiency for different vehicle speed and torque command.

### 7.4 Experimental Prototype:

Experimental prototype is developed for the IPMSM drive in the laboratory as shown in figure 16. Loss minimization algorithm is tested on the developed prototype.

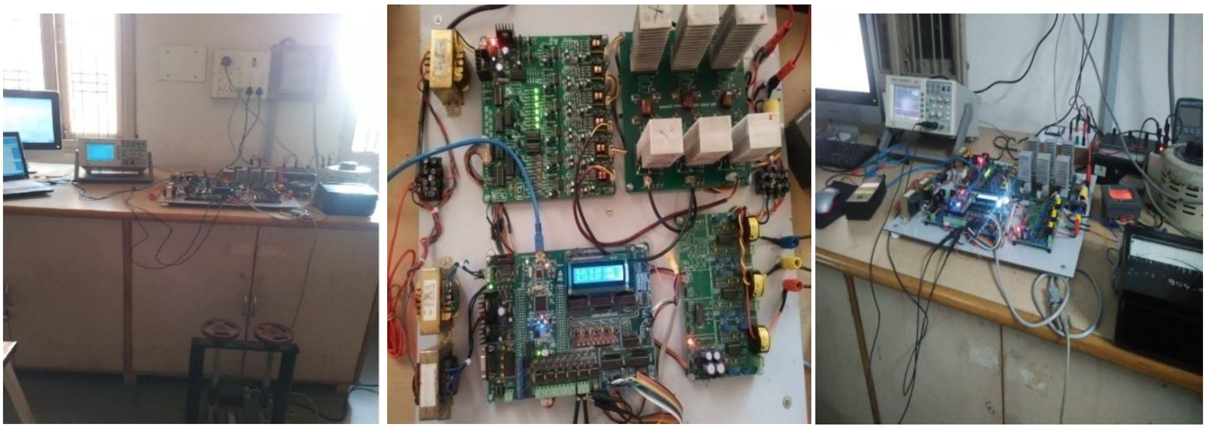

Figure 16 shows the hardware developed for IPMSM drive.

#### 7.4.1 Experimental Results :

Figures 17-19 shows the speed response of the developed prototype. Figure 16 shows the reduction in current when same system is applied with negative d-axis current.

**a) Speed response of IPMSM varying from 1000 rpm 1500 rpm to 3000 rpm at no load**


Fig. 17. 1000 rpm to 1500 rpm,

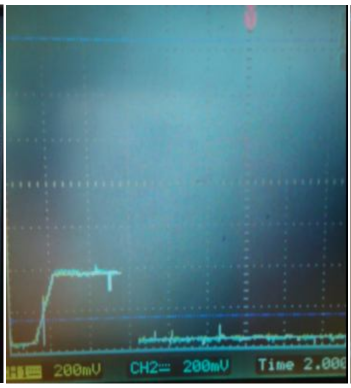

Fig. 18. 1500 rpm to 2000 rpm,

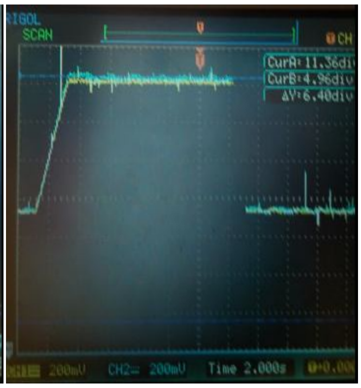

Fig. 19. 2000 rpm to 3000 rpm

**b) Motor current at id=0 and id=-0.6A for rated speed operation at no load**

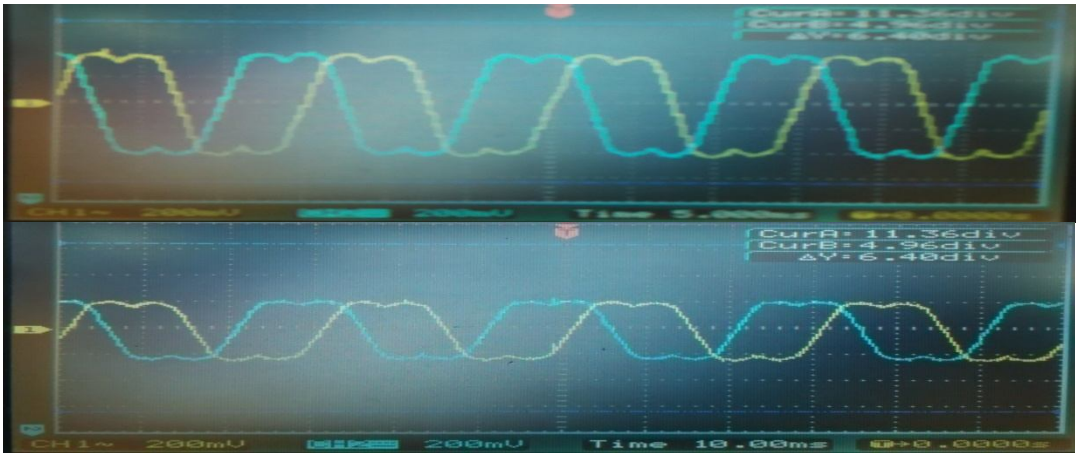

Fig. 20 Motor current at id=0 and id=-0.6A for rated speed operation at no load

Table 3. Hardware results for different value of d-axis current for 2000 rpm speed operation at reduced load

| Sr. No. | d-axis current (amp) | q-axis current (amp) | Vdc, volt | Idc, volt | Pdc, watt | Motor input power, watt |
|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 300 | 0.85 | 255 | 70 |
| 2 | -0.4 | 1.8 | 300 | 0.79 | 237 | 59 |
| 3 | -0.6 | 1.51 | 300 | 0.7 | 210 | 56 |
| 4 | -0.8 | 1.55 | 300 | 0.73 | 219 | 58 |
| 5 | -1 | 1.87 | 300 | 0.87 | 261 | 72 |
| 6 | -1.5 | 2.5 | 300 | 0.93 | 279 | 73 |

Table 3 shows the effect of d-axis current on the efficiency of IPMSM drive. This is reported as variation in the dc input power and motor input power with change in negative d-axis current. As shown in table 3, at optimizaed d-axis current of -0.6A, the system takes minimum input power for the same output power. Thus increases the efficiency of the electrical drive system if optimized d-axis current is supplied.

# 8. Achievements with respect to objectives:

Three control strategies, space vector modulation based field oriented control, space vector modulation based direct torque control and space vector modulation based direct reactive energy and torque control, are simulated using MATLAB Simulink Software without optimization and with optimization. Loss minimization based control algorithm is used for optimization of losses. Publication 3 reports the improvement in the performance of the IPMSM drive obtained by optimization for space vector modulation based field oriented control. Publication 4 reports the improvement in the performance of the IPMSM drive obtained by optimization for space vector modulation based direct reactive energy and torque control.

For battery operated vehicles, to achieve higher driving range with limited source of battery is essential. Thus main factors for the analysis are higher efficinecy and minimum torque pulsation. Comparision of results achieved by different menthods proves the superiority of optimization of space vector modulated field oriented control.

Performance of the online optimization of the designed Electrical Drive system of an electric vehicle is tested under selected drive cycle. The results proves the better performance with online optimization.

# 9. Conclusion

Simulation results are presented for conventional and optimized control for three different methods for IPMSM drive for Electric Vehicles. Results demonstrated the efficiency of IPMSM drive under various loading conditions for different control strategies. Results prove that FOC-SVM for IPMSM drives offers better efficiency and minimum torque pulsation thus that FOC-SVM with optimization of losses for IPMSM drive is a better option for Electric Vehicle application. The proposed online optimization method improves system efficiency by reducing the losses of the Electrical Drive under different driving conditions of Electric Vehicle. Experimental results of the efficiency improvement with FOC-SVM optimization control proved better performance of the IPMSM drive. Increase in efficiency of the electric drive for Electric Vehicle by even small number is important as it increases the battery life and driving range of Electric Vehicle.

## 10. List of all publications:

1. 'A Review on Control Strategies of Electric Vehicle Propulsion System', **published in Indian Journal of Technical Education (Special Issue), 3rd National Conference on Emerging Vistas of Technology in 21st Century**, ISSN:0971-3034, Pages: 85-90, 14-15 April '12.

2. 'State-of-art of optimal efficiency control of PMSM drive for Electric Vehicles', **International Conference** on Power Electronics & Renewable Energy Systems (ICPERES - 2014), April 24-26, 2014 **in association with Springer and IEEE Madras** section. Organized by: Rajalakshmi Engineering College, Chennai

**3. '**Optimize Performance of Interior Permanent Magnet Synchronous Motor for Electric Vehicles transportation system', **IEEE International Conference on Intelligent Transportation Engineering (ICITE 2016) Singapore**, August 20-22, 2016
Publication: IEEE Explore, **DOI:** 10.1109/ICITE.2016.7581335
**ISBN Information:**
**Electronic ISBN:** 978-1-4673-9048-4
**USB ISBN:** 978-1-4673-9047-7
**Print on Demand(PoD) ISBN:** 978-1-4673-9049-1

**4. '**Efficiency Analysis of Direct Reactive Energy and Torque Control-Space Vector Modulation of Interior Permanent Magnet Synchronous Motor Drive',
6th International Conference on Innovative Trends in Engineering, Life Science and Business which is being held on 10th September, 2016 at Chennai, India
**Publication: Indian Journal of Science and Technology**
**Indexed in: Scopus, ISI & Web of Science**, ISSN: 0974-6846

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