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An Integration of Virtual, Experimental & Hardware-in-loop Simulation Techniques for an Effective Assessment of DTC/FOC Motor Control Algorithms for Hybrid Electric/Fuel Cell Vehicle Application

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Abstract: Understanding of complex engineering and mathematical transformations is a prerequisite before implementation of Direct Torque and Field Orientation Control Strategies in Real Time Environment. Mathematical models of DTC / FOC are developed from concept to operate in off line simulation environment. Comparative study is carried out to understand implications of DTC & FOC on overall performance of electric drive train while negotiating different driving cycles. Dual mode motor control strategy viz. V/f + DTC and V/f + FOC is proposed to improve drivability and to maximize efficiency of electric drive train.

In development of HEV, complete electrical drive train assisted with power electronics need to build mathematically to understand the response of control strategies to Torque and Speed demand during cycle negotiations. This also felicitate in reducing the risk of discovering any error in the stage of implementation of control on actual hardware. Electric drive performance simulation is carried out with developed controls using real time platform d-SPACE RTI 1104. Hardware - In–Loop (HiL) technique is used for evaluation of these algorithms in real time environment. This is followed with an experiment performed in lab on 3 kW Induction motor with down scaled data of demand torque and speed using DTC and FOC to validate these controls experimentally.

Keywords: HEV: Hybrid Electric Fuel Cell Vehicle, DTC: Direct Torque Control, FOC: Field Orientation Control, HiL: Hardware-in-Loop Simulation, IM: Induction Motor

INTRODUCTION [1]-[2]

Selection of electric drives and its control strategies for HEV system is an utmost important step towards freezing out overall technical specifications and performance expectations. Major parameters to focus are efficiency, response, reliability and cost of drive train. Selecting an appropriate propulsion system for HEV is challenging task. At present, the induction motor is economical drive for HEV application followed by PMSM / BLDC & SRM.

The major performance requirements of HEV propulsion are summarized as follows:

- High & Flat torque at low speeds for starting and climbing
- Availability of surplus tractive effort throughout the speed range for better accelerations
- Constant power region for wide speed range after base speed of drive to felicitate use of lesser number of gear ratios especially in electric mode of driving
- High efficiency for regenerative braking
- High reliability for various vehicle operating conditions
- Reasonable cost

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Dual mode motor control strategy is used to take advantage for a better performance and improved drivability of vehicle. V/f control will be used during start –stop operations due to its ability to provide high torques in shortest period. Also to drive various accessories electrically when ICE is off, V/f is used due to its simplicity & comparable steady state performance with other control strategies. In dual mode, it has been proposed either to use DTC or FOC along with V/f depending upon vehicle operating demands. During accelerations mode & for running vehicle at Max speed, DTC is used due to its fast response in terms of torque settling time. FOC has brought into picture typically in part load transient operations which occur during city driving cycle conditions. This is to improve Torque per unit Ampere & hence improving efficiency to maximize SoC of battery.

Passenger car fitted with downsized ICE (base vehivle) is simulated for its performance in hybrid mode of operation. NEDC and US FTP highway cycles are used to build a common control strategy of electrification. Data set is generated which comprises of engine / motor torque and speed vs time which belongs to operating points lying on these cycles using developed electrification control strategy which is common for both cycles. Developed DTC and FOC motor control algorithms performance is tested first in offline environment for accessing their effectiveness while delivering torque and speed as demanded during NEDC and FTP cycles.

HiL set up is used to test these controls on real time platform. Induction motor plant model from dSpace is used for this simulation. Developed controls are deployed on MicroAutoBox coupled with RapidPro Hardware for generating PWM signals. After verifying HiL performance, experiments are performed on 3kW IM with downscaled data of torque and speed generated over driving cycles.

DEVELOPMENT OF CONTROL STRATEGY FOR ELECTRIFICATION [1]-[2]

NEDC mainly comprises of City driving pattern plus some part of High way driving cycle touching max speed of 120 km/hr. While in FTP Highway cycle, most of the time vehicle runs with full load conditions demanding high torque at higher speeds. Common electrification control strategy resulted in operating vehicle in an electric mode for those operating points which lie below 25% of max engine torque and engine speeds correspond to vehicle speed till 25 km/hr. For operating points which lie within 25 - 75% of max engine torque and engine speeds corresponds to vehicle speed above 25 km/hr, vehicle will run with ICE mode which is the efficient zone for engine under consideration. Operating points which fall above 75-100% of max engine torque, engine is restricted to operate with 75% of max torque and remaining buffer 25% torque will get complimented by torque produced by an electric motor. This is in true sense a Hybrid Mode. Apart from motor provides surplus 10% torque on overall full load torque requirement of vehicle to get better accelerations.

This is called as a booster mode. Vehicle performance simulation algorithm is used for implementing those control strategies. Electric motor operating points in terms of Torque and Speed v/s time will come as

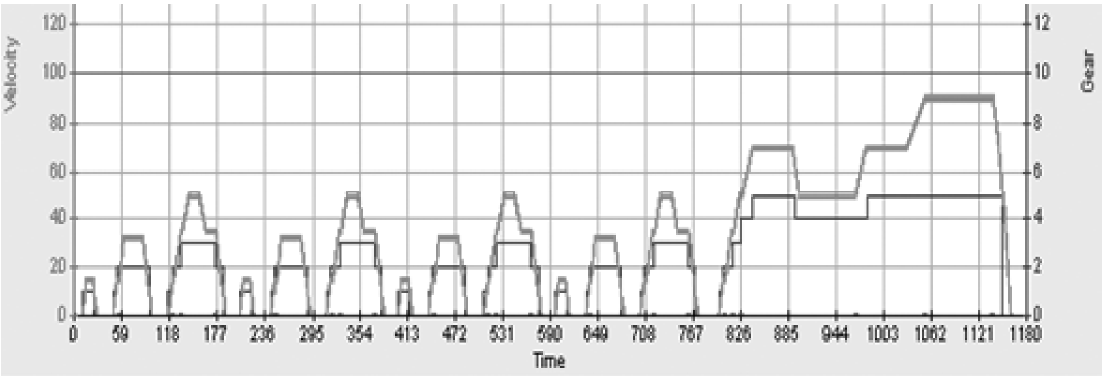


Figure 1: Nedc Driving Cycle

an outcome of this exercise to build look up table and act as an input for MCU operations. Fig. 1 & 2 shows a typical NEDC & FTP Highway driving cycles used.

Fig 3 shows developed Electrification Control Strategy for HEV under consideration. Using this strategy, electric motor operating points Torque and Speed demand while negotiating NEDC and FTP Highway driving cycles are generated. It can be seen that upto 25 % of throttle position, EM is in operation. While between 25-75% of throttle position ICE is in operation. Above 75% of throttle position both EM and ICE will deliver Torque at respective speeds.

Fig.4, 5, 6 & 7 shows demand Torque and Speed over a period of time (NEDC/FTP Highway cycle) which is expected to be delivered by an electric motor. This is nothing but a data set which will act as an input to motor control algorithm to generate PWM signals. These PWM signals in turn operate six IGBT's of three phase inverter to generate variable frequency three phase voltage output. This inverter output is fed to IM to get desired torque and speed.

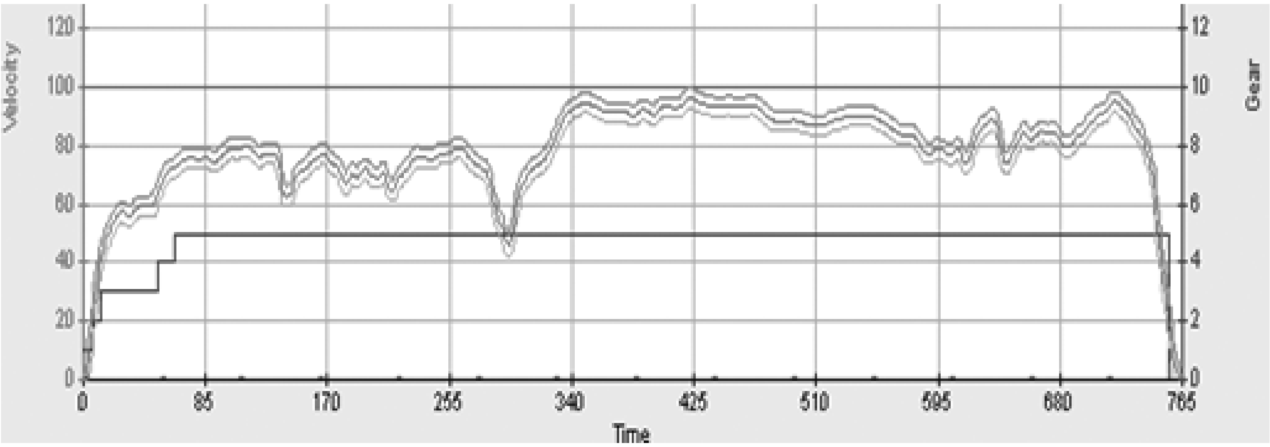


Figure 2: FTP Highway Driving Cycle

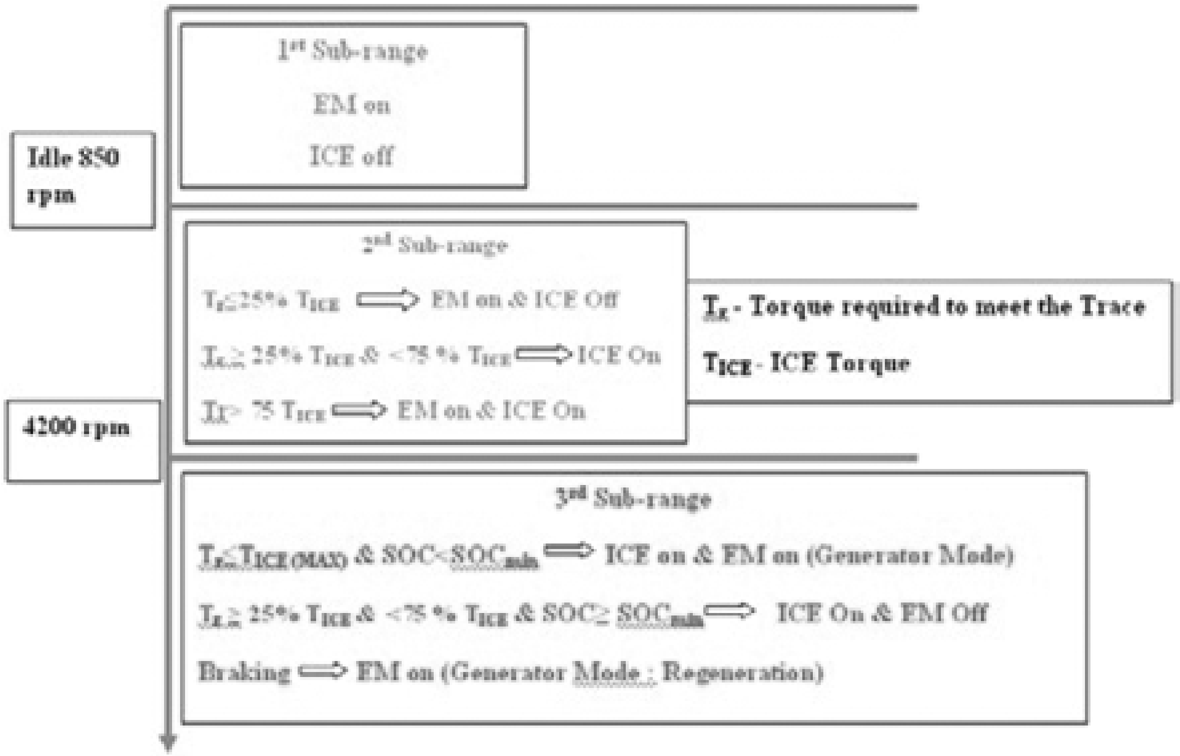


Figure 3: Full Parallel Hev Control Strategy

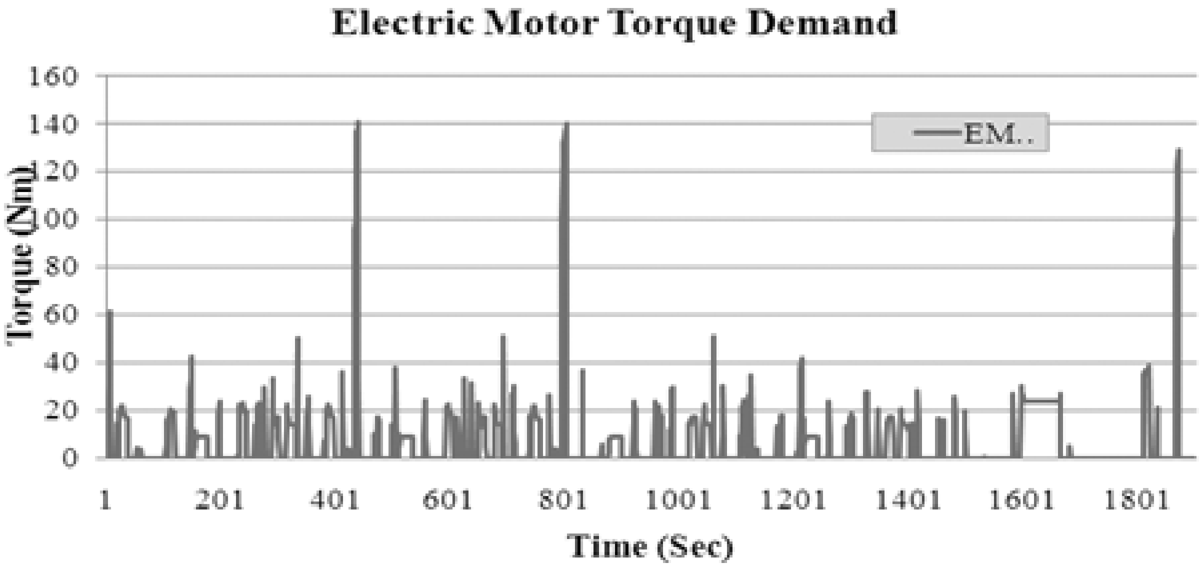


Figure 4: EM Torque Demand (NEDC)

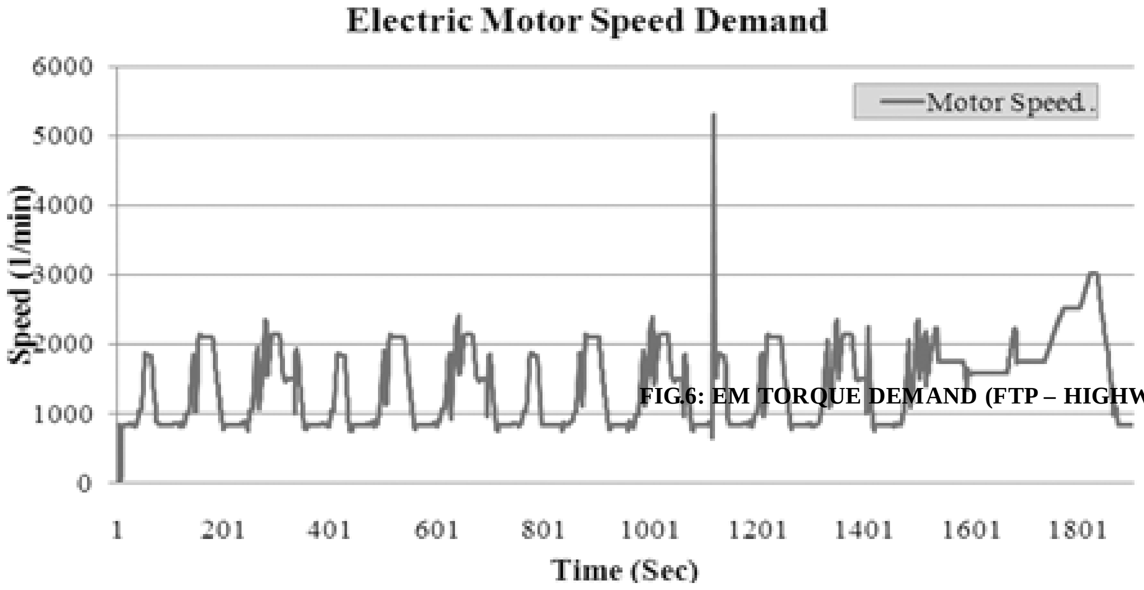


FIG.6: EM TORQUE DEMAND (FTP – HIGHWAY)

Figure 5: EM Speed Demand (NEDC)

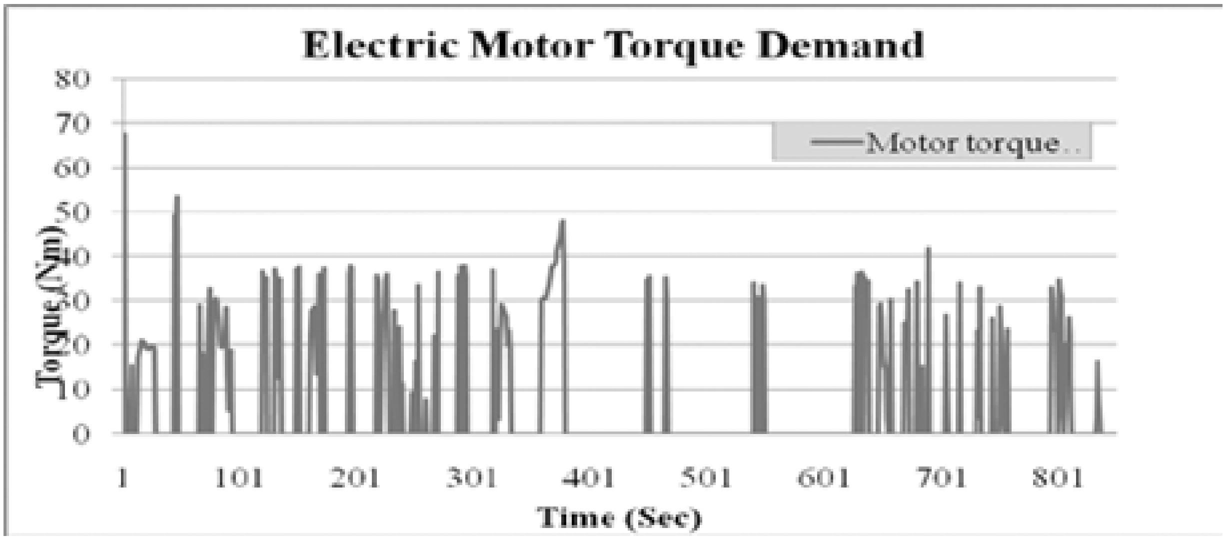


Figure 6: EM Torque Demand (FTP–Highway)

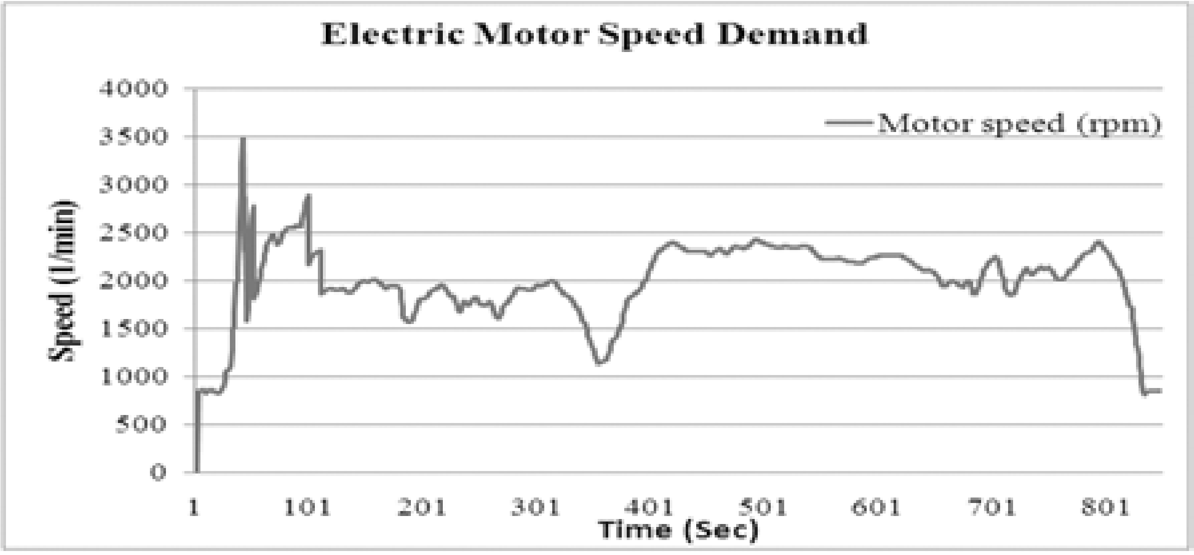


Figure 7: EM Speed Demand (FTP- Highway)

CHARACTERIZATION OF PERFORMANCE OF AN ELECTRIC DRIVE [3]

For EV and HEV most commonly used electric drives are DC, Induction Motor, PMSM, and SRM. Out of which simplest and economical one is IM. Though PMSM offers better efficiencies, it is costlier due to use of heavy earth magnetic materials. On performance side PMSM stands above IM due to its varying power factor w.r.t load. In case of IM, power factor is always lagging and less than unity.

This makes PMSM more efficient and possesses Torque energy density than IM.

SRM is simple in construction. But it’s having complicated motor control algorithm apart from its noisy signature due to higher torque ripples.

A brief comparison of performance parameter rating of various electric drives is given below in Table 1.

Table 1
Performance Ratings Of Electric Drives

Parameter	*DC*	*IM*	*PM*	*SRM*
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Sum Total	22	27	25	23

Hence, Induction Motor is considered as an electric power plant candidate for proposed full parallel HEV configuration. Fig.8 shows cluster of operating points (torque & speed) generated during negotiation of NEDC cycle which need to be fulfilled by electric drive selected. By considering pure electric motor operation as one of the operating mode, full load torque curve characteristics is generated over a complete speed range of operation. It is ensured that all operating points generated over negotiating NEDC and FTP driving cycles fall well below this full load characteristic. This ensures buffer tractive effort availability to meet enhanced acceleration requirements in different gears. An IM with 4 pole configuration having base

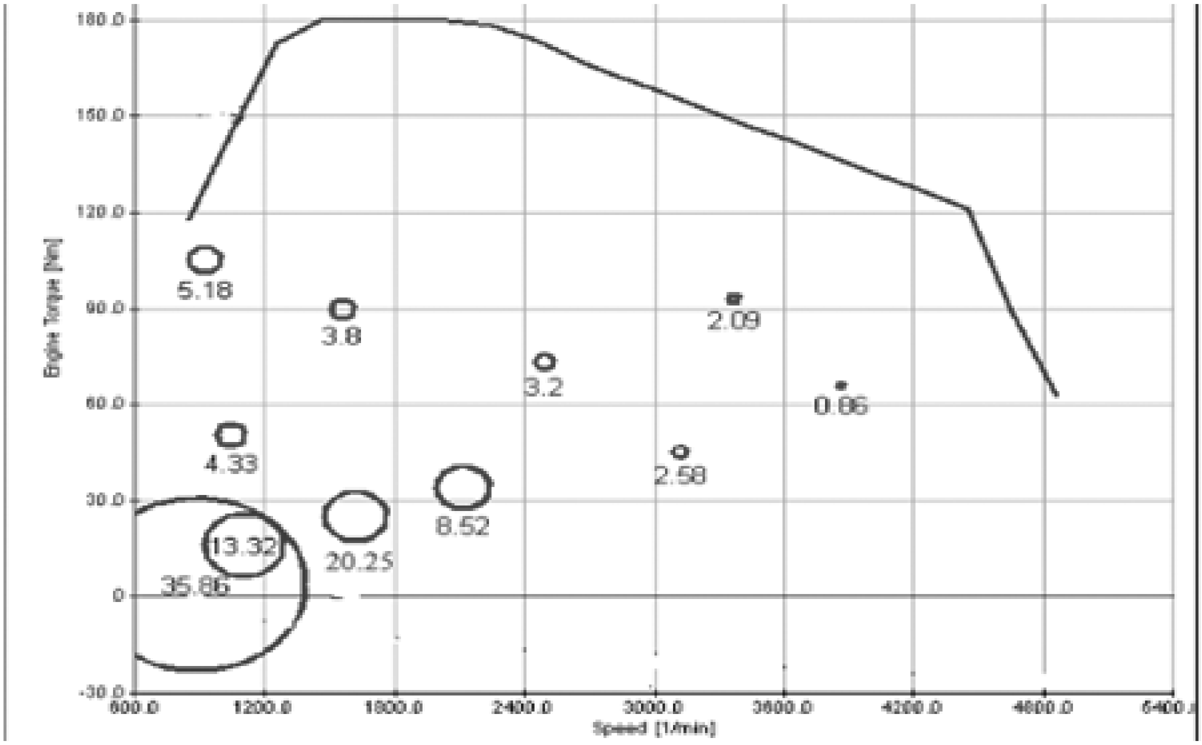


Figure 8: Full Load Torque Curve Characterization For IM and Weighted Average Operating Points (NEDC)

speed of 2200 rpm, delivering flat power of 45 kW in the speed range of 2200 – 4500 rpm is an outcome of this requirement.

DEVELOPMENT OF MOTOR CONTROL ALGORITHMS [4] – [5]

Efforts are made to build motor control algorithm from concept to understand complex interaction of 3 phase variables which need to control precisely to get desired stabilized output in shortest time step. A common algorithm which is base for implementation of three classical controls is built by referring three

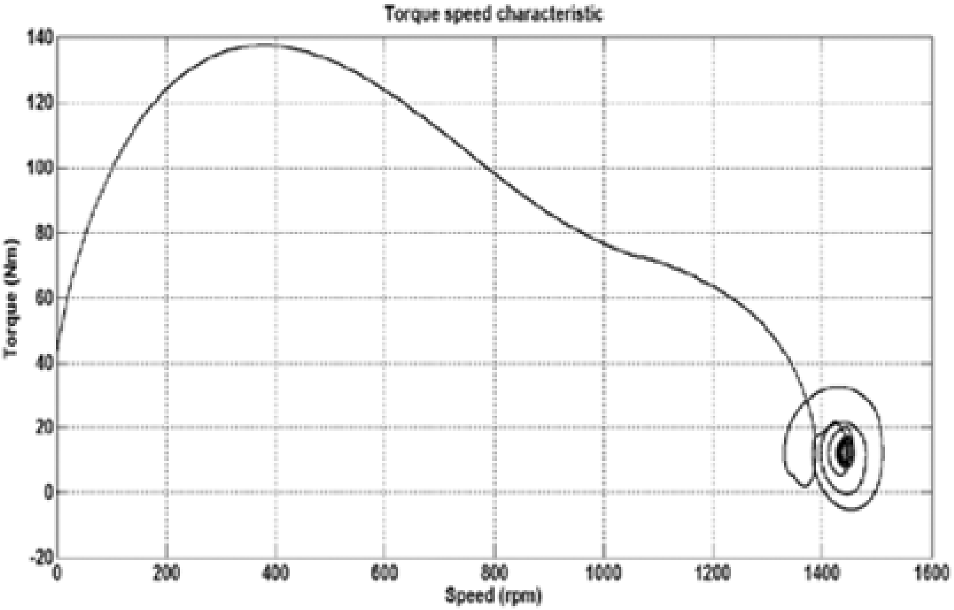


Figure 9: Converged And Stabilized Torque & Speed Operating Point

phase variables (stator & rotor) into two phase variable system. This is Clarke's (d-q) transformation. Voltage is being considered as an independent variable and linked with two dependent variables viz. Flux and Current and thus linked with a transfer matrix having elements as resistances, mutual and magnetic inductances. These equations are solved by using finite difference and state variable approach. Thus for any instance by knowing instantaneous three phase voltages we can compute electromagnetic torque and speed whose convergence criteria greatly depend on three phase voltage sampling time and no of cycles taken for computation. Fig.9 shows converged torque and speed for supplied input three phase voltage with Frequency corresponding to required speed.

A) V/F + Direct Torque Control

(Higher Accelerations but with less Efficiency)

V/f (Full Load Performance / Start – Stop Operations / Driving Accessories when ICE is off) **:** A dual control strategy is developed to deliver full load and part load demands over a speed range on NEDC and FTP driving cycles. First dual control strategy is a combination of V/f Control (Ref Fig 10.) for full load operating points and Direct Torque Control for part load operating points. Referring Fig.8, it can be seen

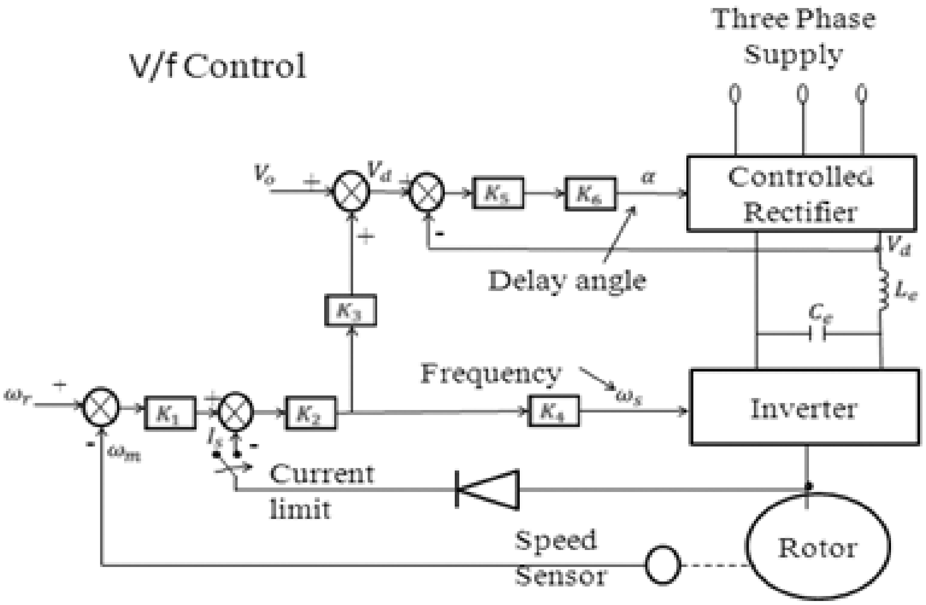


Figure 10: V/F Control - Mathematical Block Set

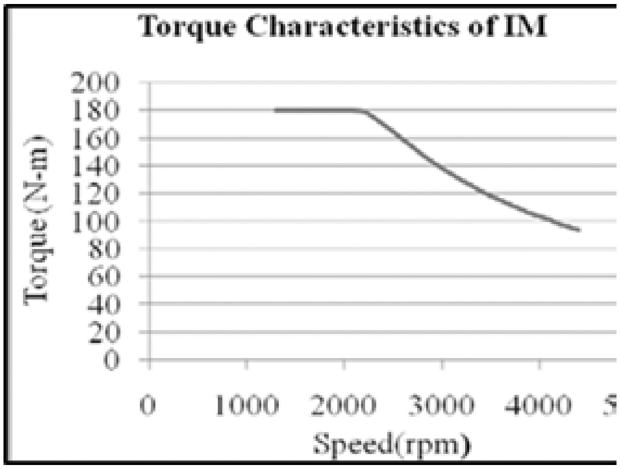


Figure 11 (a): V/F + Optimized Full Load Torque Curve

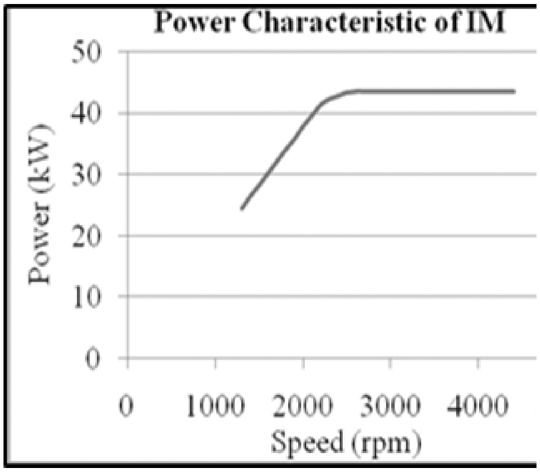


Figure 11 (b): V/F + Flux Weakening Mode Control Resulted in Flat Power Zone

that from 1200-2200 rpm, a flat torque is obtained by increasing Voltages and frequency with a constant ratio. Refer Fig.11 (a) for the same. By the time when speed reaches to 2200 rpm, voltage level reaches to its rated value. This ensures a constant flux region in this zone which is responsible for a flat torque curve response. In order to extract benefit of ideal tractive effort delivery characteristics, a flat power curve after base speed till rated speed is desired. This is accomplished by keeping voltage to its rated value but as the speed is increased beyond, flux weakening operation is performed. This is done by increasing frequency of supply. Flux weakening happens due to increase in inductive losses as frequency increases. This phenomena controls induction of back EMF and hence reduction in rotor flux. This ensures rise in torque which reflects in delivering a constant power zone.

Fig.11(b) shows a flat power zone characteristic of proposed IM. This type of combined flat torque and power characteristics offers usage of single or two speed transmission as against multi gear transmission in case of electric mode of operation. However we can use DTC alone instead of V/f to generate this full load characteristic but at the cost of increase in settling time of torque w.r.t time.

Direct Torque Control

DTC is latest vector drive control. A mathematical code is built on top of core code which computes converged and stabilized Torque & Speed operating point for a given voltage input. A look table is generated which comprises of demand Torque & Speed v/s time over NEDC and FTP Highway cycle during electric mode of operation.

Two level, six leg Half Bridge Inverters eight switching states are computed to get desired 3 phase output to meet Torque and Speed demand as per look up table. Fig. 12 shows possible eight voltage vectors in d-q plane which can be generated by switching six IGBT’s in a particular sequence to generate three phase voltages to feed an electric power as desired. Frequency of supply voltage is computed based on speed to be achieved and slip characteristic of IM under consideration.

In a DTC drive, flux linkage and electromagnetic torque are controlled directly by the selection of optimum inverter switching modes.

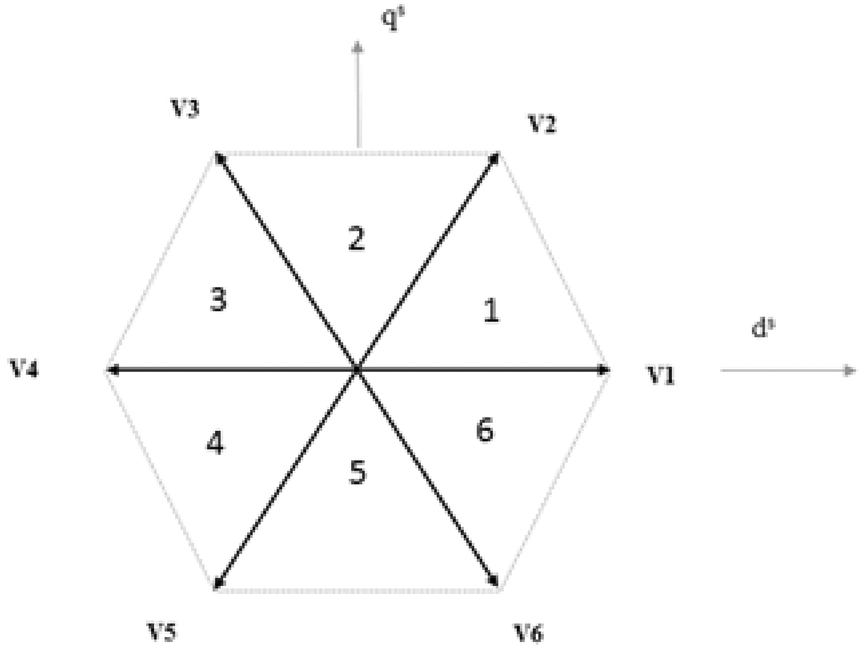


Figure 12 (a): Voltage Vectors Corresponding to Eight Inveter Switching States & Plotted On D-Q Plane.

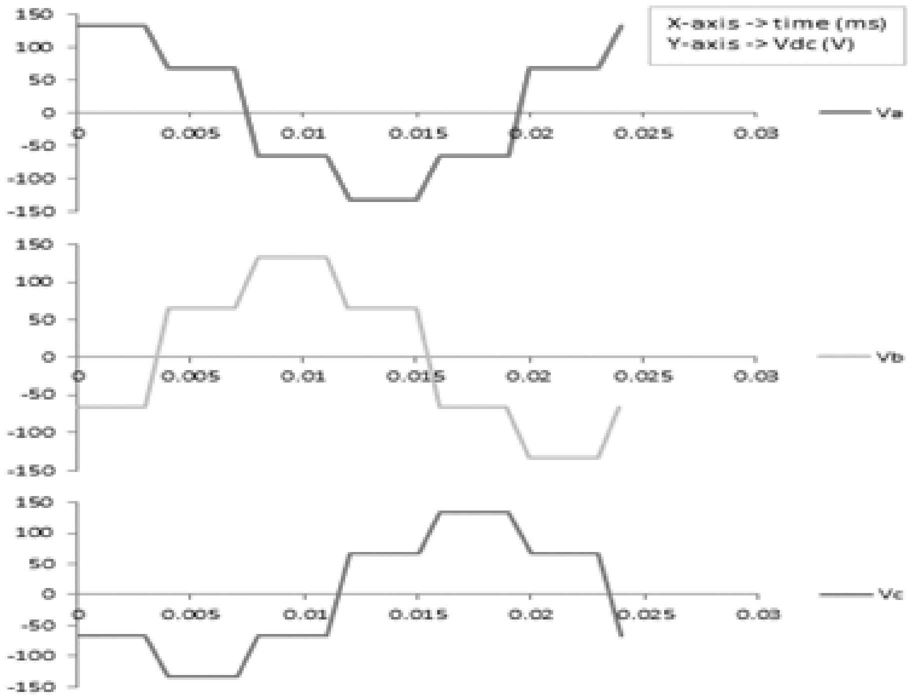


Figure 12 (b): Phase Voltages (Va, Vb, Vc) Obtained For A Complete One Rotation Of State Vector (Input: Vdc = 220v; F = 40hz)

Table 2
Logic Matrix For Inverter Switching State Selection

		Counterclockwise Rotation					
	Counterclockwise	*Sec 1*	*Sec 2*	*Sec 3*	*Sec 4*	*Sec 5*	*Sec 6*
Inc Flux	Inc T(01)	100	110	010	011	001	101
(0)	Dec T(00)	000	111	000	111	000	111
Dec Flux	Inc TY(01)	110	010	011	001	101	100
(1)	Dec T(00)	111	000	111	000	111	000

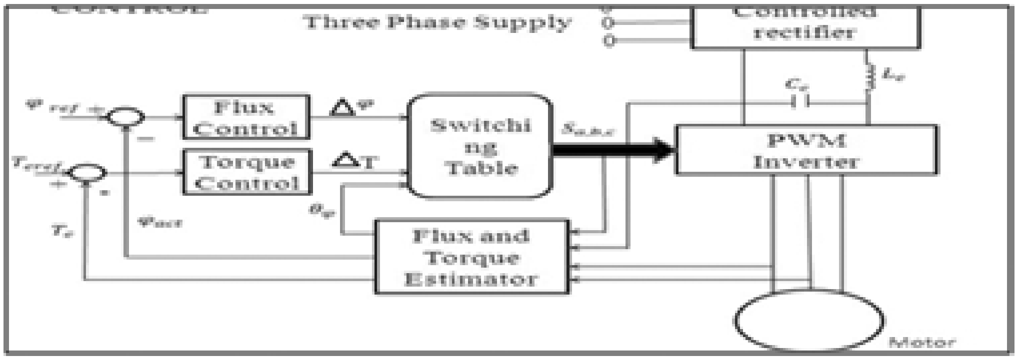


Figure 13: DTC Computation Block

The selection is made to restrict the flux linkages and electromagnetic torque errors within the respective flux and torque hysteresis bands, to obtain fast torque response, low inverter switching frequency and low total harmonic distortion contents. The required space vectors can be selected by using so-called optimal switching-voltage vector look-up table. (Refer Table2).

Fig.13 shows Computation block for selection of optimum inverter switching state using DTC algorithm. Tuning of PID controller parameters along with estimation of no load flux at different operating speeds is most important step for getting correct information of Torque (T*) and flux (¸*). After this step T* and ¸* are compared with demand T and ¸ in three level and two level hysteresis band controller for Torque and Flux respectively. Knowing this information along with sector information for the previous flux vector position, optimum space vector will be selected from Logic Matrix (Ref. Table 2). Once appropriate vector selection is made, from that instance we have to keep applying next vectors in anti-clockwise or clockwise rotation (depending to increase or decrease torque and flux) to get desired 3 phase voltage to get converged & stabilized Torque and Speed output as required

In the process of control of torque and flux by selecting space voltage vectors, we are also computing current and flux vectors which are rotating in both directions (depending upon whether we have to increase or decrease torque and flux). If we plot these positions in d-q plane, we can generate locus by connecting tips of these vectors (Refer Fig.15).

Band width of this locus tells about how rapidly variation in energy put into system has happened to get desired output. Fig.16 shows computed three phase currents while tracing NEDC cycle using DTC algorithm.

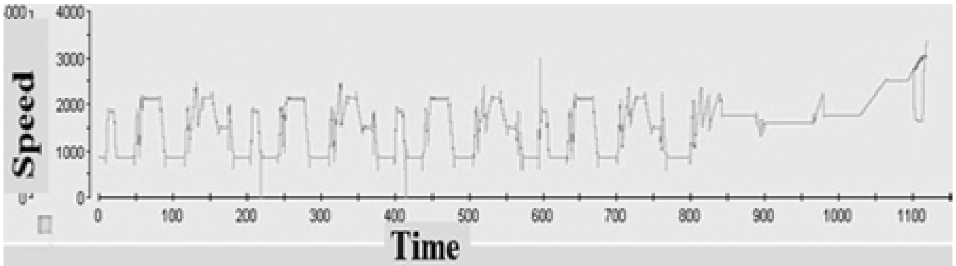


Figure 14 (a): Torque (N-M) And Speed (RPM) Response: Nedc Cycle (DTC Strategy)

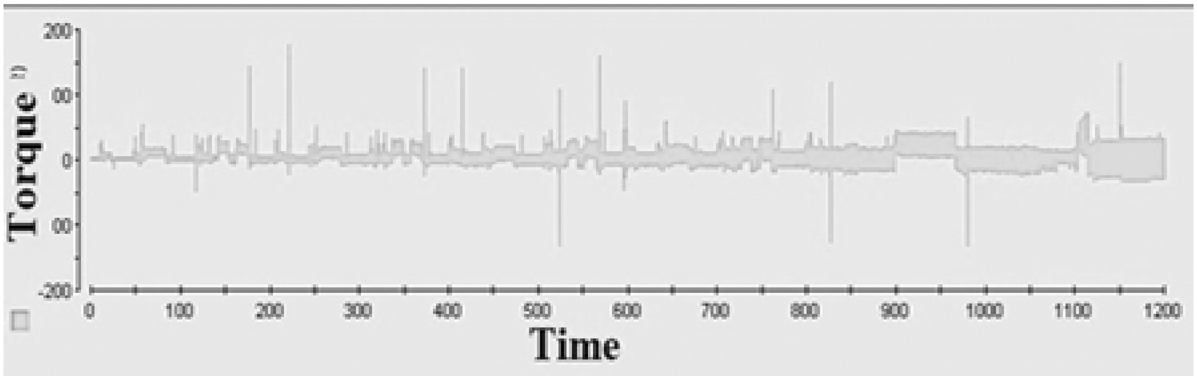


Figure 14 (b): shows delivered electromagnetic Torque and Speed response by motor during negotiating NEDC Cycle using DTC control strategy.

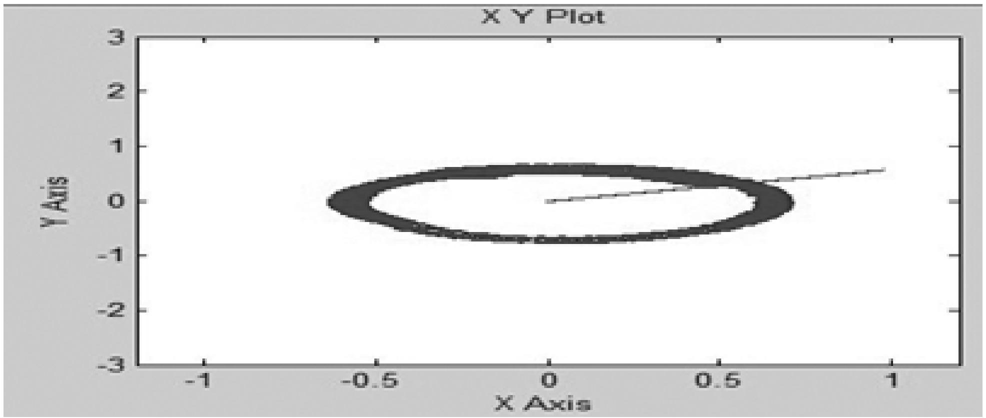


Figure 15: D-Q Flux: Nedc With Dtc (A Locus Generated By Flux Vector in D-Q Plane)

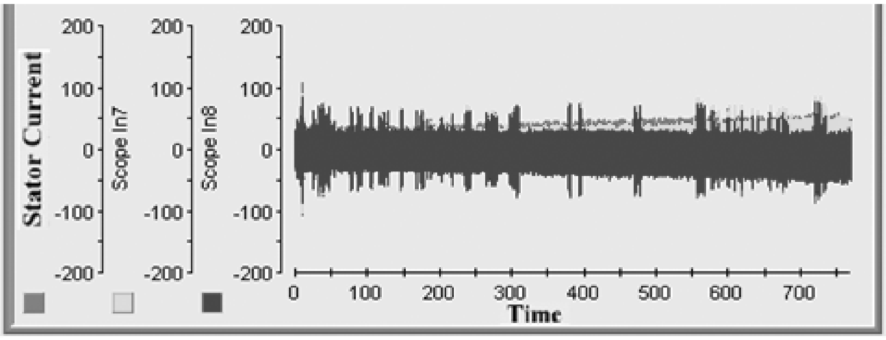


Figure 16: Three Phase Currents (Nedc With Dtc)

B) V/F + FIELD ORIENTATION CONTROL

(Efficient Driving: Part load transient operations with maximum Torque / Ampere)

In this dual mode control strategy, V/f is used only in Start / Stop operations and to drive various accessories when in ICE is switched off again for the reason of simplicity in control and availability of quick and more torque required during start operations.

Field Oriented Control:

In Both V/f and DTC there is an inherent coupling between filed and rotor currents. This is mainly due to fact that asynchronous motors operate on mutual induction effect. For prediction of transient performance simulation, one has to solve differential equations in which inductances are varying w.r.t. time. This fact makes control of these machines more complex and even response is sluggish due to the coupling effect present. This introduces instability in output response which is more detrimental in case of HEV applications. Also to get desired response with a greater accuracy, any attempt of control may lead over or underestimation of feed phase voltages. This leads for lower Torque / Ampere and hence control becomes less energy efficient.

In order to maximize Torque / Ampere along with better output stability, we should have control similar to separately excited motor. Here both field and armature windings are separately excited. Also orthogonality

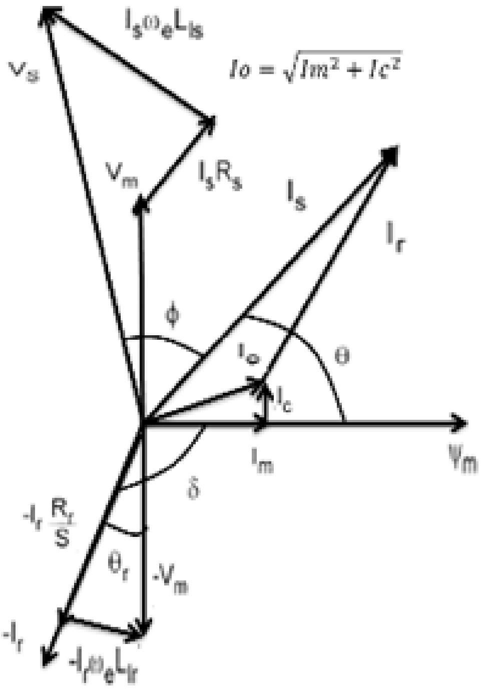


Figure 17: Phasor Diagram For IM

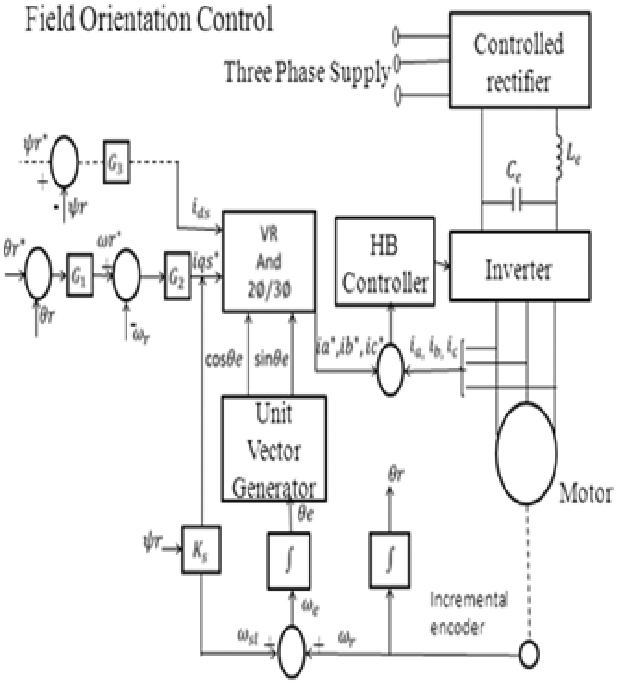


Figure 18: Foc Computation Block Set

between these two currents is maintained by a mechanical commutator. Thus a precise control either by controlling filed or armature current is obtained that to maintain orthogonality. Both these facts improve stability in output and maximize Torque / Ampere, hence proving control as energy efficient.

In steady state orthogonality is always maintained between stator and rotor currents. Ref Fig. 17 (Angle between Im and Ir is 90 + ⊖r). In unsteady state due to time varying inductances, angle between two synchronously. Rotating frame of references (Stator flux φm and rotor flux φr - Aligned with Ir) changes which is nothing but angle 90 + ⊖r. This change in angle is called as slip angle.

In order to maintain this orthogonality, an additional transformation is performed on two phase stator and rotor variables which is obtained by Park Transformation. Both d-q axis are rotated by an angle which is equal to slip angle. Thus all stator and rotor variables are now transformed into a new frame of reference called as Excitation Frame of reference. By doing this, sinusoidal quantities start appearing into DC quantities. Hence control will resemble as like control of DC separately excited motor.

This transformation indirectly takes care of change in inductance due to unsteady state, since we are using actual rotor flux information using Hall sensor to compute slip angle.

Thus exact amount of energy required by precisely knowing change in inductance information can be computed and applied. This ensures both stability and precise current for getting demand torque. Hence FOC is more energy efficient control as against other controls.

Fig.18 shows Computation Block Set for implementation of FOC. Error to first PID is computed by taking difference of intermediate speed (which arises due to application of torque) and demand speed. Another error input required for second PID is computed by knowing flux at intermediate speed (arrived after application of torque) with no load condition and then multiplying it by ratio of demand speed to present speed. Both PID are tuned to give as an output as id and iq as DC quantities. These are further transformed through inverse Clarke transformation to get ia*, ib*, ic* as three phase currents.

These three phase currents are again compared by considering as reference currents with actual currents. Sinusoidal PWM technique in the form of Hysteresis Band Controller is used to adjust gate signals of IGBT of Inverter to get demand Torque and Speed.

Fig.19 shows delivered electromagnetic Torque and Speed response by motor during negotiating NEDC Cycle using DTC control strategy.

Fig. 20 shows locus of demand flux vector generated during execution of NEDC cycle with FOC.

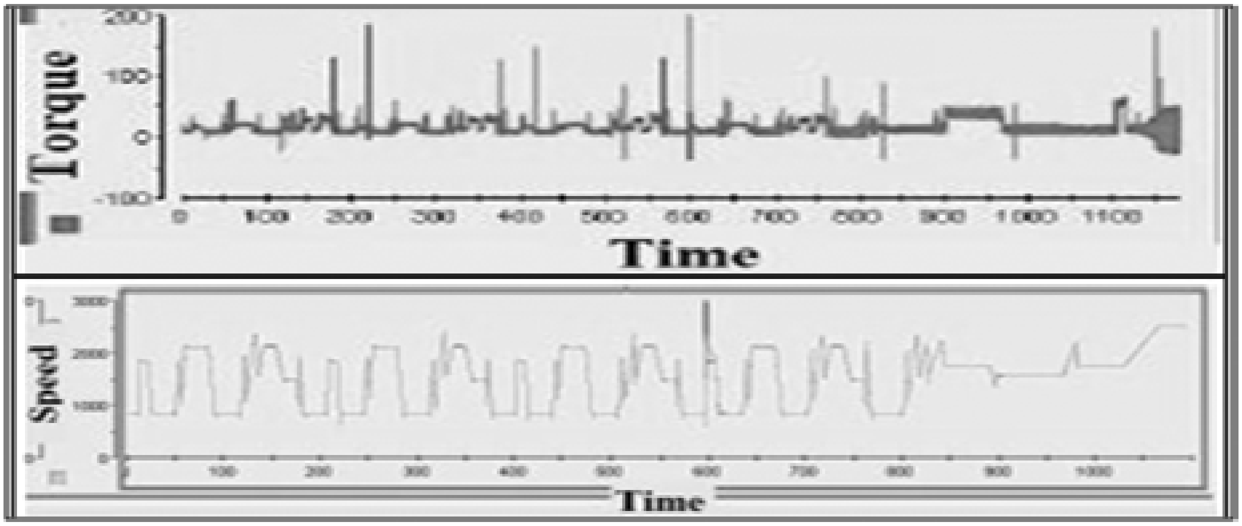


Figure 19: Torque (N-M) & Speed (RPM) Response of FOC For Nedc Driving Cycle

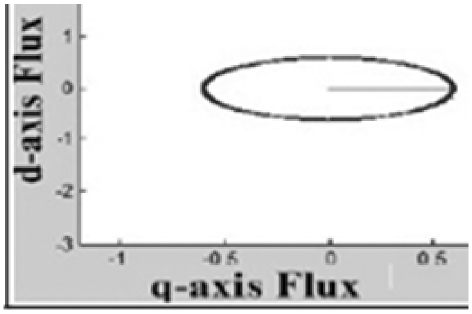


Figure 20: D-Q Flux: Nedc With Dtc (A Locus Generated By Flux Vector In D-Q Plane)

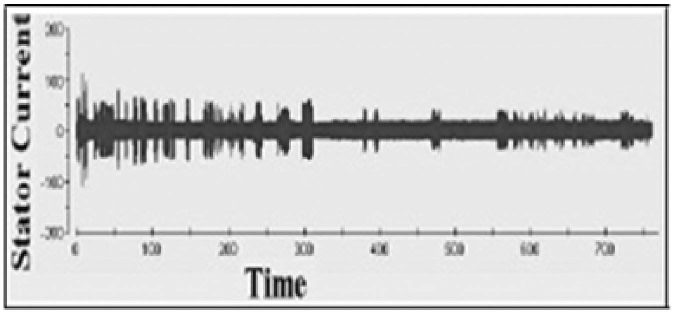


Figure 21: Three Phase Currents (NEDC With FOC)

Fig.21 shows three phase stator currents required to fulfill demand Torque and Speed while negotiating NEDC with FOC

HARDWARE-IN-LOOP SIMULATION [6]

After obtaining desired response using in house developed motor control algorithms, need is felt to extend this exercise first by deploying these control strategies on real time microcontrollers and to assess its performance using HiL Technique.

The dSPACE HiL system is high performance digital control system works in a close loop manner and is based on the MPC8240 processor and the TMS320F240 DSP processor, I /O interface boards which are

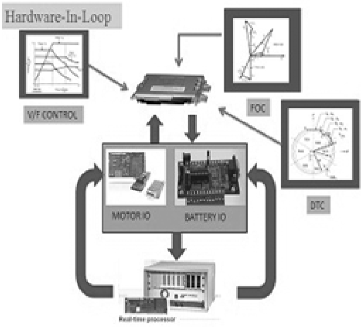
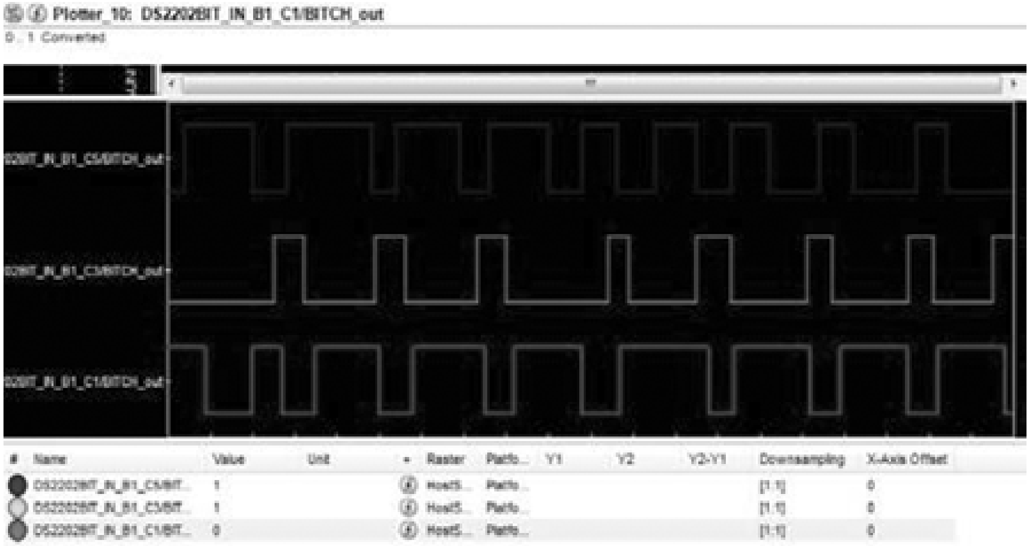


Figure 22: Hil Simulation Environment

Figure 23: Hil– Experimental Set Up



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○	DS2202BIT_IN_B1_C3/BIT...	1		ⓕ	Host5...	Platfo...				[1:1]	0
●	DS2202BIT_IN_B1_C1/BIT...	0		ⓕ	Host5...	Platfo...				[1:1]	0

Figure 24: Gating Signals: Micro Auto Box Out Put

part of simulator, a breakout panel and the software tools. Ref. Fig.22 for HiL set up with real time Micro Controller in loop for testing of motor control algorithms. The output of the ECU will be a low power Pulse Width Modulated (PWM) pulses that will be fed to operate IGBT's of the soft Inverter to get desired 3 phase variable voltage. Motors mathematical model will generate electromagnetic torque and speed as per real time demand along with three phase currents, fluxes. Feedback of current and speed signals are feed forward to ECU as an input reference parameters.

For this work, in place of real time ECU, MicroAuto Box is used for running the developed control algorithms.

Fig.24 shows gate signals generated by Micro Auto Box for initial fraction of seconds of driving cycle.

Fig.25 shows three phase currents and d-q flux generated. Computation of èe is most critical while implementing FOC. Fig.26 shows èe variation as cycle progresses.

These results are very much in line with offline simulation as well as output of indigenously developed motor control algorithm coupled with Induction Motor Performance prediction. Based on the correlation obtained on virtual and HiL, its proved that developed control strategy is delivering output in V/F, DTC as well as FOC modes.

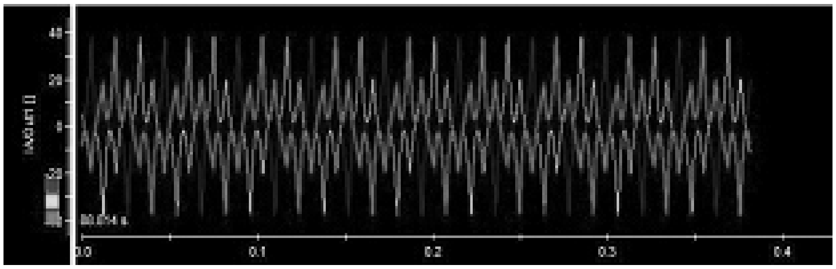

Figure 25: Phase Currents – Plant Model Output

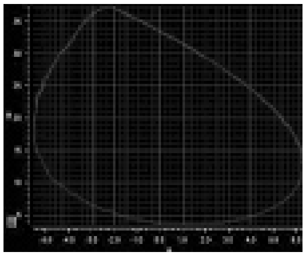

Figure 26: D-Q Flux - Plant Model Output

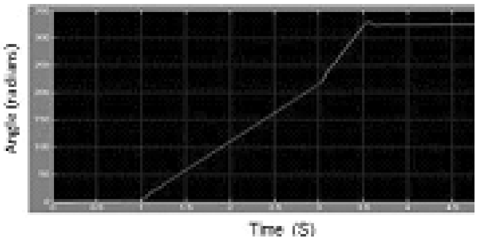

Figure 27: ⊖e Variation W.r.t. Time: Plant Model Output

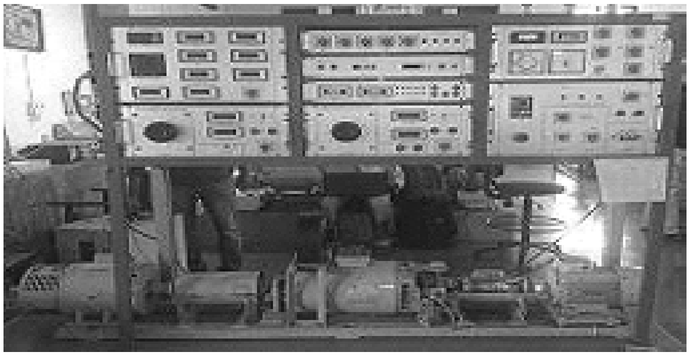

Figure 28: Experimental Set-up

EXPERIMENTAL

Followed by HiL simulation, experimental testing of IM with scale down look up table (data of torque & speed demand) and IM specs is done to ensure robustness of control strategy before implementing it on real HEV

Table 3
IM Specifications

Sr. No	*Parameter*	*Specification*
1	Type of Motor	Induction
2	Rated Power	3 Kw @ 4000 rpm
3	Max Torque	14 N-m @ 1500 rpm
4	Base Speed	1500 rpm
5	Stator resistance	5.2Ω
6	Rotor resistance	5.92Ω
7	Stator inductance	0.03676H
8	Rotor inductance	0.03676H
9	Mutual Inductance	0.92H
10	No of Poles	4

A 3 kW induction motor is connected through the VSI. This is built by using IPM module (PEC16DSM01). The switching signals which are available from the DSP board are interfaced to IGBT based voltage source inverter. The output of the inverter is connected to the induction motor. The signals, currents and voltages from the terminals are captured by using sensors. These are fed back to DSP board. Motor connected to transient dynamometer to generate demand torque and speed as per the look up table. All three control strategies are tested and a satisfactory output response is obtained with this scaled down experiment.

CONCLUSION

Efforts are made to develop motor control algorithms from concept viz V/f, DTC and FOC. A dual motor control strategy is proposed for HEV under consideration. It will be either V/f + DTC or V/f + FOC. In both modes V/f will be used only for those operating points which will lie on Full Load Characteristic of Motor / Start- Stop / driving accessories when engine is in off condition.

Use of DTC is proposed in case of Fun to Drive Concept. i.e. in case of getting higher accelerations during driving cycle negotiations. With DTC mode, both NEDC and FTP cycles have got very closely traced. However, it can be seen that current consumption is more with DTC mode.

FOC mode is proposed for transient part load (city driving) conditions where there is no requirement of sharp accelerations. FOC have given better current consumption in the range of 10 – 15 % as against with use of DTC.

Thus blending of dual control strategy viz. V/f + DTC , V/f + FOC is developed from concept to get better accelerations on highway operations as well as improving current consumption during city driving conditions.

Use of HiL Technique have shortened development time and gave confidence before running motor experimentally using loading on transient dynamometer.

FOC strategy found more efficient in terms of getting more Torque / Ampere. However DTC found more responsive but at the cost of more amperage. This has resulted mainly due to more Total Harmonic Distortion (THD) content in ouput voltage from inverter when ran with DTC mode.

Thus integration of Virtual, HiL and Scaled down experimental work has helped in understanding complexity of implementation of these algorithms followed by laying a robust methodology of development & testing of controls before putting on vehicle level.

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