Nine-Switch Converter Fed Dual Mechanical Port Machine for Hybrid Electric Car

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Abstract—Concern of environment leads more interest in de-velopment of electrical and hybrid electric vehicles. Now a day's new topologies of machine are introduced in electric and hybrid electric vehicles to reduce its weight and size. One of such machines is Dual mechanical port machine (DMPM). This single machine can replace electric motor, generator, planetary gear set in a conventional HEV and there by reduction of weight and size. This paper presents a nine-switch (NS) converter with reduced number of switching devices fed DMPM suitable for Hybrid electric car with the aim of further reduction of overall size. DMPM suitable for Toyota Prius hybrid electric car is designed and the performance is analysed using Ansys Maxwell. NS converter fed DMPM for hybrid electric car is modelled in MATLAB Simulink platform and compared its performance with conventional back to back (BB) converter fed DMPM for Hybrid electric car. It is observed that performance of both converters is more or less same. So, NS converter can be replaced with conventional BB converter and there by further reduction of weight and size can be obtained.

Index Terms—Dual mechanical port machine, nine-switch converter, Back to back converter, Hybrid electric vehicle.

I. Introduction

A conventional vehicle solemnly depends upon internal combustion engine (ICE) for converting chemical energy into mechanical energy required for the wheel. Increasing environ-mental concern leads growing demand on electric and hybrid electric vehicles (HEV). A HEV combines two energy sources, ICE and electric motor. Based on its component's configu-ration HEV is mainly classified into series, parallel, series-parallel configurations. In a series-parallel HEV, required power for starting the wheel is given by battery through an electric motor and when the highest efficiency point of ICE is reached, can couple it to the system. And also, during breaking kinetic energy of the vehicle can be stored as electrical energy with generator. Such a configuration improves efficiency and decreases pollution level but the configuration with electric motor, generator and planetary gear set increases the weight and size of the vehicle. This configuration can be replaced with a single component called DMPM which consists of two rotors and a stator.

Various possible structures of DMPM is discussed in [2][3]. It can also function as an electric variable transmission (EVT) [4]. DMPM can be used in different application such as washing machine [5], wind power generation system [6], hybrid electric vehicle [7], etc. Focus of this paper is in the area of hybrid electric car. DMPM is an efficient, compact and simple structure to use in HEV [8]. Control strategies and multi operation modes of DMPM used for HEV is discussed in [9]. Detailed control strategy of DMPM is discussed in [10].

From the literature review it is observed that researchers have not focused on space reduction through power electronic converter area for DMPM based HEV. So, simply used conven-tional BB converter having twelve number of semiconductor switches [2][7][8]. By reducing number of semiconductor switches and their accessories further reduction of weight and size of HEV is possible [1]. Therefore, in this paper introduce a NS converter having nine semiconductor switches fed DMPM, thereby reducing overall weight and size of HEV.

Design and analyse performance of a NS converter fed DMPM for a hybrid electric car and verify that its performance is comparable with BB converter fed DMPM for hybrid electric car is the main objective of this paper.

This paper is organised as in second section DMPM based HEV is discussed. Different converter topologies for DMPM based HEV is discussed in section III. Design of DMPM using Ansys Maxwell for Toyota Prius hybrid electric car is pre-sented in section IV. In the fifth section modelling of DMPM with NS converter in MATLAB is presented. Simulation and performance evaluation of NS converter fed DMPM for hybrid electric car and comparison with BB converter fed DMPM is in section VI. Conclusion is in section VII.

II. DMPM based HEV

Fig. 1 shows the DMPM based HEV. DMPM has two rotors and a stator. Stator is a three-phase winding and fed from a three-phase supply. Permanent magnet outer rotor is connected to the wheel of HEV. Three-phase supply is given to inner wound rotor through a slip ring. It is connected to the ICE. This machine can play the role of two machines. Stator and outer rotor together called outer machine act as permanent magnet synchronous machine. Outer rotor together with inner rotor act as induction machine and it is considered as inner machine. Both the machine can function as either motor or generator based on different operation modes of HEV [9].

DMPM based HEV consists of converter section. Converter converts ac to dc and store it in battery when the machine act

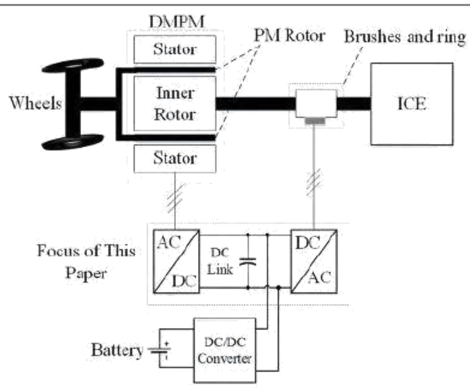


Fig. 1: DMPM based HEV structure [1].

as generator. It also converts dc to ac when the machine act as motor.

III. CONVERTER TOPOLOGIES FOR DMPM BASED HEV

DMPM requires two independent three phase supply for sta-tor and wound rotor. Conventionally a BB converter connected to a dc bus having twelve number of semiconductor switches are used to feed two electric ports of DMPM based HEV. A five leg converter with only five legs available to supply two three-phase outputs having ten semiconductor switches can also use for this purpose [1]. A NS converter having nine semiconductor switches can also be used for same purpose as shown in fig. 4 [1]. It can further reduce size and weight of the overall system as it has lesser number of semiconductor switches than other two converters.

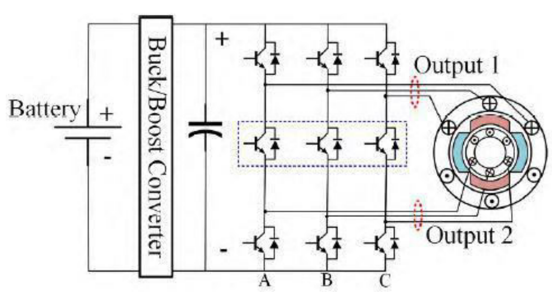


Fig. 2: NS converter fed DMPM based HEV [1].

IV. DESIGN OF DMPM

Worlds one of the progressive hybrid electric car is Toyota Prius 2004 and it is chosen for further study. For calculating power requirement of a vehicle, vehicle dynamics such as gradient resistance, rolling resistance, aerodynamic drag,etc has to be considered. Force and power required for driving a vehicle is represented by Equations (1)-(6).

$$F_{total} = F_r + F_g + F_{ad} + F_a \quad (1)$$

$$F_r = C_{rr} M\, g \cos \alpha \quad (2)$$

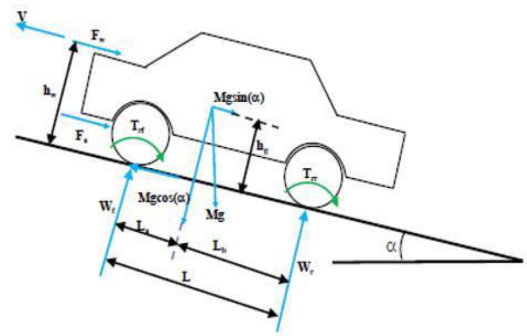


Fig. 3: Forces acting on a car.

$$F_g = M\, g \sin \alpha \quad (3)$$

$$F_{ad} = \frac{1}{2} C_D A_f \rho V^2 \quad (4)$$

$$F_a = [M + \sum (J_{rot}) / r_{dyn}^2]\, dv/dt \quad (5)$$

Total power

$$P = \frac{F_{total} V}{3600} \quad (6)$$

Where F_{total}; F_r; F_g; F_{ad} and F_a are the total force, force due to rolling resistance, force due to gradient resistance, force due to aerodynamic drag and force due to acceleration respectively. C_{rr}, M, g, α, C_D, V, A_f, ρ, J_{rot} and r_{dyn} are the coefficient of rolling resistance, mass in kg, acceleration due to gravity, road angle, drag coefficient, vehicle speed, vehicle front area in m^2, density of air, inertia of rotational component and dynamic radius of the tyre in m respectively. Table I shows specification of Toyota Prius 2004 [8]. Forces and power required for Toyota

TABLE I: Specifications of Toyota Prius 2004 [8]

	Specifications	Value
Vehicle	Weight	1360 kg
	Length	4450 mm
	Width	1725 mm
	Tyre Diameter	0.3556 m
	Coefficient of rolling resistance	0.015
	Drag coefficient	0.26 Ns^2/kgm
	Maximum vehicle speed in electric mode	60 km/h
	Maximum vehicle speed in hybrid mode	160 km/h
Engine	Maximum power	57 kW @ 5000 rpm
Planetary gear	Ratio (ring, planet, sun)	2.6 (78/23/30)
Final gear	Ratio	4.113
Electrical motor	Maximum power	50 kW
	speed	6000 rpm
	torque	400 Nm
Electrical generator	Maximum power	30 kW
	speed	1000 rpm
	torque	400 Nm
Battery	Type	NiMh
	Module number	28
	Nominal energy, voltage	1.3 kWh, 201.6 V

Prius hybrid electric car is calculated using the equations (1)-(6) are shown in table II. A standard electrical machine design

TABLE II: Forces and Power

$F_{rolling}$	F_{ad}	F_a	F_{total}	Power
197.08 N	223.26 N	702.3 N	3437.05 N	81.1 kW

procedure reported in [11] is applied to obtain the dimensions of the DMPM. The input parameters of the design procedure and power rating of the machine is selected same as that of in Toyota Prius [8]. By using the values obtained from the

TABLE III: Dimensions and rating of DMPM

Parameters	Value
Stator outer diameter	445.4 mm
Stator inner diameter	326 mm
Axial length	256 mm
No of slots	48
Slot width	8 mm
Slot depth	24 mm
Airgap length	1.3 mm
Outer rotor outer diameter	323.4 mm
Outer rotor inner diameter	283.8 mm
Magnetic thickness	5mm
No of poles	8
Airgap length	0.708 mm
Inner rotor outer diameter	282.38 mm
Inner rotor inner diameter	125mm
No of slots	48
Slot width	5 mm
Slot depth	23 mm
Rated power	50 kW
Rated voltage	500 V
Rated current	50.2 A
Rated Torque	640 Nm
Rated speed	750 rpm

design equations which are shown in the table III, a model of DMPM is designed in Ansys Maxwell. Analysed the designed machine in Ansys Maxwell 2D. 2D model of the machine is shown in fig. 4. When supply is given to stator rated power and torque is obtained as shown in fig. 5 and 6.

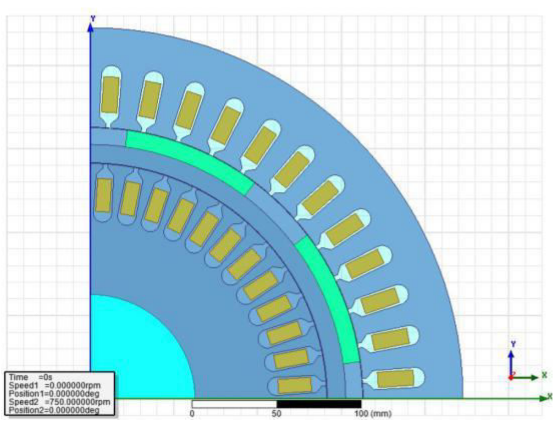


Fig. 4: 2D model of the machine.

V. MODELLING IN MATLAB/SIMULINK PLATFORM

DMPM is modelled using the dynamic equations reported in [7] in MATLAB Simulink platform. Values of Parameters for modelling are obtained from Maxwell analysis and are

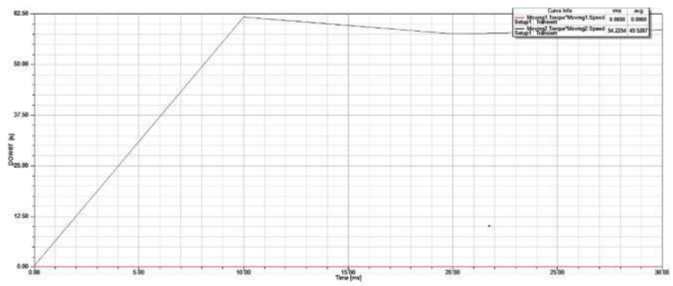


Fig. 5: Power.

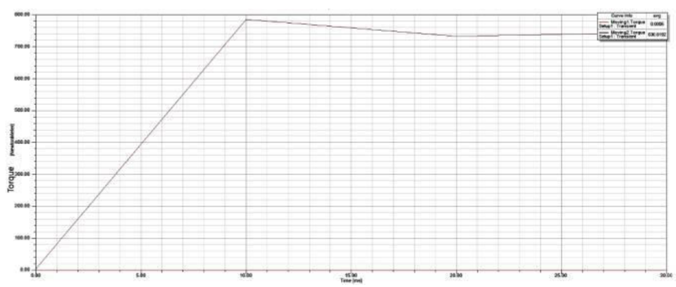


Fig. 6: Torque.

shown in table IV. A NS converter fed DMPM is modelled in MATLAB Simulink platform as shown in fig. 7. For performance comparison a BB converter fed DMPM also modelled in MATLAB.

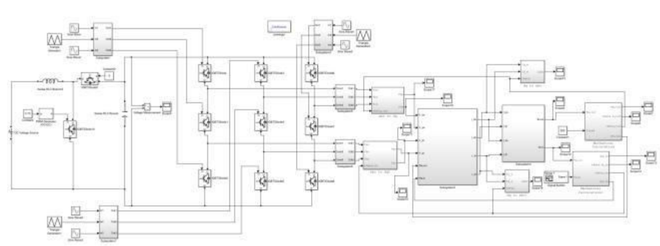


Fig. 7: MATLAB model of NS converter fed DMPM.

VI. SIMULATION RESULTS

Without any closed loop controller NS converter fed DMPM is simulated and the results are compared with BB converter

TABLE IV: Modelling parameters

Parameters	Value
r_s	0.7722
r_r	0.125251
L_{md}	1.27e-4 H
L_{mq}	3.81e-4 H
λ_{m1}	0.8 Wb
λ_{m2}	0.75 Wb
L_{sd}	5e-3 H
L_{sq}	11.5e-3 H
$L_{rd}=L_{rq}$	11.5e-3 H
$J_{in}=J_{out}$	0.8e-3 kg.m^2
B	0.001

fed DMPM. During starting ICE efficiency is low so, initially ICE is not powered (fig. 8). Three phase supply is given to stator only. A load torque of 500 Nm is applied to represents the vehicle inertia. Outer rotor runs at rated speed of 750 rpm as a PMSM (fig. 9). Inner rotor runs as an induction motor with a slip of 0.05% for NS converter fed DMPM and 0.038% for BB converter fed DMPM (fig. 10). Torque developed in the outer rotor of DMPM supplied through NS converter and BB converter are shown in fig. 11. Both are comparable.

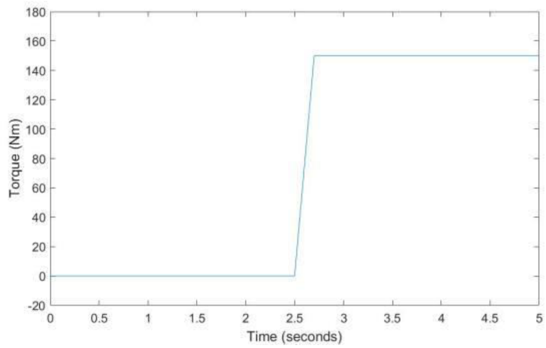
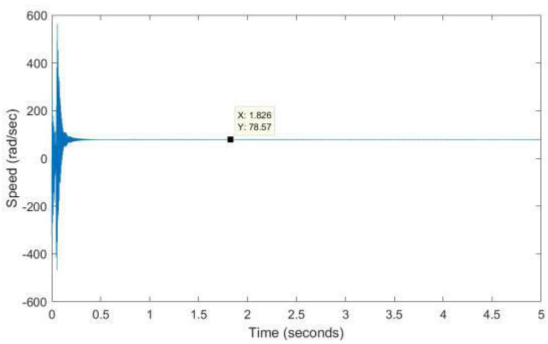
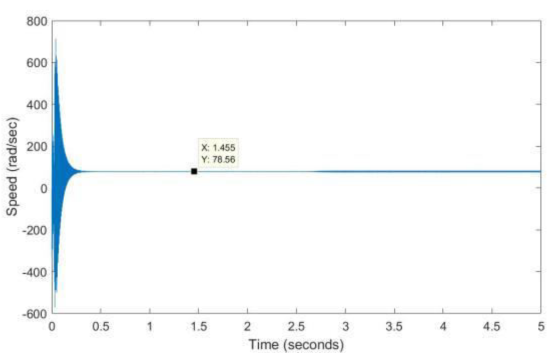


Fig. 8: Torque from ICE.



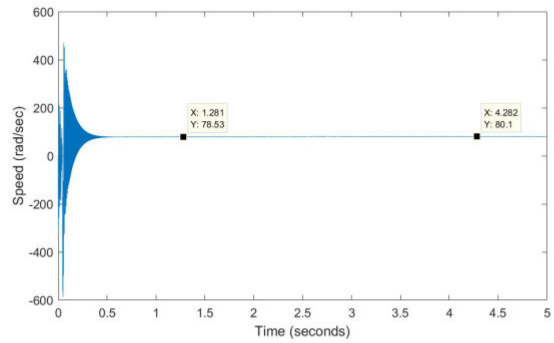
(a) Nine-switch converter fed DMPM



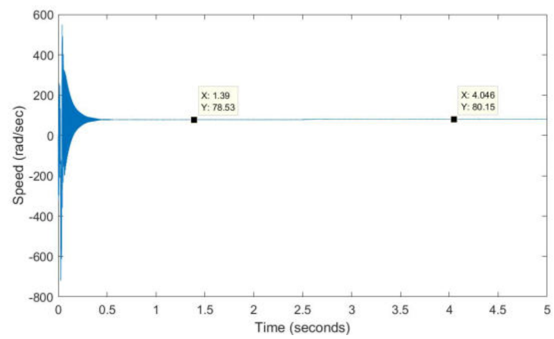
(b) Back to back converter fed DMPM

Fig. 9: Outer rotor speed.

At 2.5 second vehicle is accelerated through ICE. Inner rotor speed increases and runs as an induction generator with a slip of -1.9% for NS converter fed DMPM and -2% for

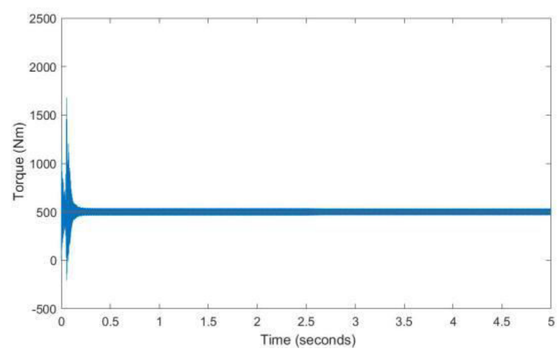


(a) Nine-switch converter fed DMPM

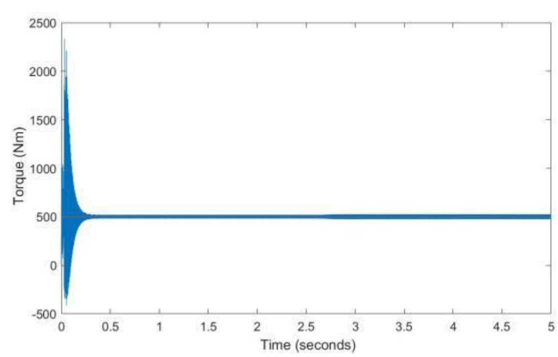


(b) Back to back converter fed DMPM

Fig. 10: Inner rotor speed.



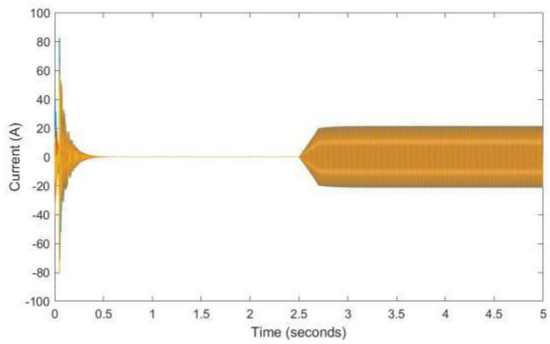
(a) Nine-switch converter fed DMPM



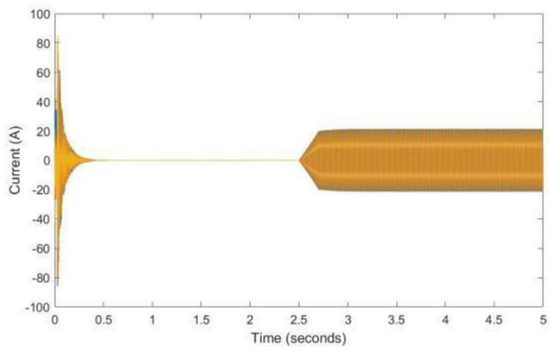
(b) Back to back converter fed DMPM

Fig. 11: Outer rotor torque with load torque.

BB converter fed DMPM and generate current (fig. 12). This current can be stored in the battery.



(a) Nine-switch converter fed DMPM



(b) Back to back converter fed DMPM

Fig. 12: Inner rotor current.

VII. CONCLUSION

Researches to reduce size and weight of electric and hybrid electric vehicle growing attention to DMPM. Design of this machine for Toyota Prius hybrid electric car is done and analysed in Ansys Maxwell software. Modelling of NS con-verter fed DMPM for hybrid electric car is done in MATLAB Simulink platform and performance is compared with BB converter fed DMPM. From result analysis it is observed that the performance of NS converter fed DMPM is comparable with BB converter fed DMPM and hence BB converter can be replaced with NS converter for DMPM fed HEV to get further reduction of weight and size, as it consists only 9 switches where as BB converter has 12 switches. As the dc link voltage required in NS converter is double as that of BB converter capacitor size required is high which is a limitation of the proposed system.

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