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Modeling and Simulation of an Integrated Starter Generator Based on PMSM with SVPWM Strategy for Engine Starting and Battery Charging

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Abstract - The modelling and simulation of an integrated starter generator (ISG) system with 48 and 12-volt DC power setup for use in automotive applications is presented in this paper. The ISG system is a key component in these applications, providing both engine starting and battery charging capabilities. A mathematical model of the ISG system is developed using Simulink, and the system is simulated under various conditions with a 48- and 12-volt DC power setup. The results of the simulations are presented and discussed, highlighting the performance and efficiency of the ISG system.

***Key Words*:** Integrated Starter Generators, Flywheel mounted ISG, DC-DC 48V and 12V setup, Space Vector PWM, Permanent Magnet Synchronous Machine (PMSM), IC Engine starting and battery charging,

1. INTRODUCTION

The ISG system is an indispensable element in modern automotive operations, providing both Engine starting and battery charging competences. The design and performance of the ISG system are critical considerations in the development of these operations.

The qualifying technology that permits the development and spread of HEVs are the Power Electronics with relations of DC – DC and DC – AC power converters and varying topologies. The DC – DC bidirectional converter is necessary to associate the DC source and the AC drive. This converter requires boost operation in one way of power flow (motoring mode) and buck operation in alternative way (regenerating mode).

2. ISG SYSTEM OVERVIEW

One of the pretensions of the automotive industry is a more operative use of energy in vehicles. HEVs are implicit supporters to reduce both consumption and emissions. Hybrid powertrains use a conventional Internal Combustion Engine (ICE) in amalgamation with an electric motor, a battery, and an electronic controller.

I .The role of Integrated Starter- Generator in HEV

The electronically controlled integrated starter-generator (ISG), as its name indicates, replaces both the conventional starter and alternator (generator) in a single electric device [1]. The motives to combine the starter and alternator in a single machine of augmented power assessment are:

- A desire to exclude the starter, which is only an active element during machine operation.
- There's a need to replace the present belt and pulley coupling between the alternator and the crankshaft.
- In order to ameliorate the quality of distributed power, fast control of generator voltage during load dumps is needed.
- A desire to eliminate the slip rings and brushes found in some of wound rotor alternators. The ISG controller acts as a bi-directional power converter, changing Mechanical energy into electrical energy and vice versa [2].
- Functioning as an electric motor, it starts the ICE nearly silently and immensely faster than any conventional starter. As a generator, it produces power for the lights, the air-conditioning system, the radio, and all other electrical consumers in the automotive, but with advanced effectiveness than former systems.

II. ISG important functions

- Start-Stop
- Electricity generation and
- Power assistance.

The ISG permits the ICE to turn off and preserve energy at stops and instantly resume upon demanding the gas pedal. consequently, rather of continuing to use energy at idling speed, for case when staying at a stream of traffic light, the engine of a Vehicle with ISG switches off entirely when the vehicle is no extended in motion. When the traffic light goes green and the driver presses the throttle to move out, the ISG Vehicle starts up nearly incontinently.

In this" engine cranking" mode, the ISG can give satisfactory rotation using battery power to drive the ICE to the extreme starting speed. Once that speed is exceeded, the ISG drive power is turned off. The vehicle driver, still, won't notice any difference because the ISG system will resume the ICE autonomously.

The ISG can induce electric energy to be stored in the battery by taking mechanical energy from the revolving crankshaft of the vehicle's Engine (in power generation mode).

In addition, the ISG can similarly act as a retarding force for the crankshaft and regenerate and feed back into the battery free electric energy when braking the Vehicle(restorative braking), together when releasing the accelerator and when pressing the brake pedal(retarding power generation mode). In boost mode, the ISG can be used to support the ICE by delivering additional power for fast acceleration. ISG remains active all over the driving process, for example, all through overtaking or at other times when extra power is necessitated.

III. ISG System Overview

Fig. 1 displays the controller blocks and overall power circuit. The ISG electric drives system comprises essentially of a power electronics box and an electric machine. A bidirectional DC/DC converter and an inverter/rectifier make up the majority of the power electronics subsystem.

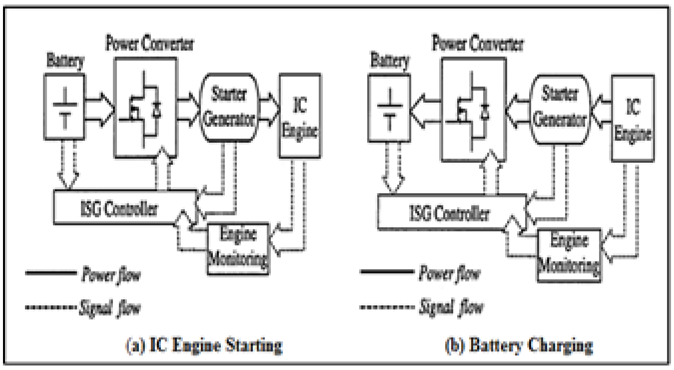

Fig.1.The overall Engine starting and battery charging operations.

A bi-directional buck-boost DC-DC converter, it delivers high voltage from the low-voltage battery pack configuration to the inverter input. Thus, the DC-DC converter serves as a boost converter when the electric machine is operating in motor mode, and it acts as a buck converter when the electric machine is operating in regeneration mode. The converter's ability to operate as either a motor or a generator account for its bi-directionality. The electric machine can be driven to the necessary speed and torque levels with the help of a three-phase inverter. The DC-DC converter charges the batteries while the inverter serves as a regulated rectifier in the regenerative mode.

3. SELECTION OF PERMANENT MAGNET SYNCHRONOUS MACHINE DRIVE

The representation of electromagnetic structures, such as rotor poles, in a PMSM, can be expanded without incurring significant degradation in machine performance. This makes PM machines popular in all forms of special applications. In addition, using PM motors or generators in electric drives makes it feasible to obtain the maximum possible efficiencies. In a well-designed PMSM, cu losses as it might be insignificant, making the architecture maximum in efficiency, The researchers have described that the PMSM is being mostly used for high-production utilization, such as automation and industrial machines, which require speed controllers that give not only good ability, high-quality, high efficiency, but also flexibility and efficiency in the construction system and implementation.

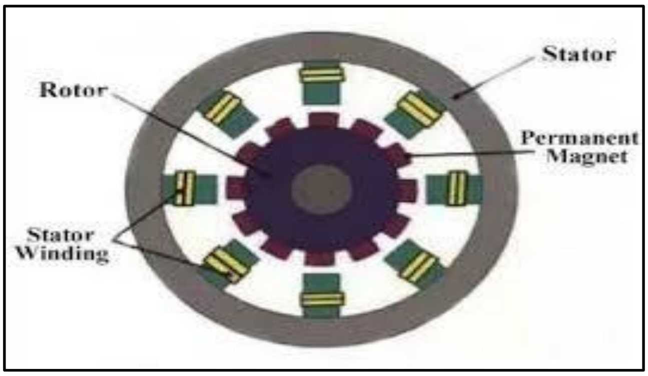

Fig.2 Permanent Magnet Synchronous Motor

Fig.2 shows basic PMSM, A Type of AC synchronous motor where the field is excited by permanent magnets that generate sinusoidal back EMF. A permanent magnet is used as a rotor to create a magnetic field. Hence there is no need to wound field winding on the motor. It is also known as a 3-phase brushless permanent sine wave motor. The permanent magnet synchronous motors are very efficient, brushless, very fast, safe, and give high dynamic performance when compared to the conventional motors[3].

I. EMF and Torque equation

In a synchronous machine, the average EMF induced per phase is called dynamic induces EMF in a synchronous motor, The flux cut by each conductor per revolution is Pϕ Weber, Then the time taken to complete one revolution is 60/N sec.

The average EMF induced per conductor can be calculated by using[3]

$$(P\phi N\ /\ 60\ )\ x\ Zph\ =\ (\ P\phi N\ /\ 60\ )\ x\ 2Tph \qquad (1)$$

$Where\ Tph\ =\ Zph\ /\ 2$

Therefore, the average EMF per phase is,

$$=\ 4\ x\ \phi\ x\ Tph\ x\ PN/120\ =\ 4\phi fTph \qquad (2)$$

$Where\ Tph\ =\ no.\ Of\ turns\ connected\ in\ series\ per\ phase$
$\phi\ =\ flux/pole\ in\ Weber$
$P\ =\ no.\ Of\ poles$
$F\ =\ frequency\ in\ Hz$
$Zp\ =\ no.\ Of\ conductors\ connected\ in\ series\ per\ phase.$
$=\ Zph/3$

The EMF equation depends on the coils and the conductors on the stator. For this motor, the distribution factor Kd and pitch factor Kp is also considered.

Hence,

$$E\ =\ 4\ x\ \phi\ x\ f\ x\ Tph\ xKd\ x\ Kp \qquad (3)$$

The torque equation of a permanent magnet synchronous motor is given as,

$$T\ =\ (3\ x\ Eph\ x\ Iph\ x\ sin\beta)\ /\ \omega m \qquad (4)$$

4. FIELD ORIENTED CONTROL (FOC)

Field Oriented controls (FOC) require a position detector, similar to a Hall Effect detector, for constantly covering the rotor position, in order to use this value to break apart the stator current in id and iq. The Hall Effect detector measures the magnitude field; the output voltage is directly commensurable to the density of the magnetic field around the

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detector. This device is made with a thin piece of semiconductor material that passes a nonstop current through itself. The external magnetic flux exerts a force on this material, diverting the charge carriers (electrons and holes) to either side of the arbor. As a consequence, a measurable voltage is generated.Fig.3. Shows Speed- based field- Oriented control scheme for a three- phase Permanent Magnet Synchronous Machine

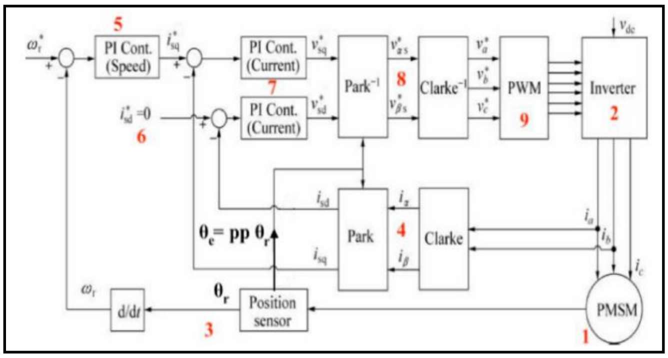

Fig.3 Speed-based field-oriented control scheme for a PMSM

In fig.3.Represented elements are:

1. The SPMSM;
2. The inverter for driving the motor;
3. A sensor for measuring the actual rotor mechanical angular position $\theta r = \theta m$ and a derivative block for obtaining the actual angular speed ωr. The electrical angle θe is obtained from θr by multiplying it by the number of pole pair's pp;
4. The Clarke-Park transformations for computing the direct-quadrature stator current from the three-phase current in abc reference frame. For this mathematical block, the measurement of the actual electric angle is needed – the value θe is obtained from θr. Thanks to this decoupling action, the feedback stator currents id and iq are controlled as DC quantities and are compared with the reference values $id*$ and $id*$ through subtractions;
5. The PI regulator is used for obtaining the reference quadrature stator current $iq*$ from the rotor speed error. Alternatively, from the speed error the reference motor torque $T*$ can be obtained and then this value is converted into $iq*$. As described in previous chapter, a SPM synchronous machine, there is a proportional dependence between torque and quadrature current in the constant torque region, through the torque constant kT;
6. The reference direct stator current $id*$ is always equal to zero because the flux-weakening region is not considered for extending the range of rotor speed values;
7. The PI controllers are used for estimating the reference dq voltage values from the direct and quadrature current errors;
8. The Clarke-Park inverse transform blocks are then used for computing the three-phase reference voltage $vabc*$ from the direct-quadrature values $vd*$ and $vq*$;
9. Finally, a PWM (or alternatively a SVPWM) technique is implemented based on the three-phase reference voltages, and the outputs of this block are sent to the inverter.
10. As simplification for the vector control used for the project, the three-phase reference waveforms $va*$, $vb*$ and $vc*$ are used for directly driving the synchronous motor, without inserting the inverter. In fact, within the Lab VIEW development environment ideal configurations are considered for the PMSM and the applied control strategy.

This method is very useful for application where wide speed range i.e., from zero to maximum speed is required and where full torque is needed to be produced even at the zero-speed operation. In this method there are two constants as an input reference: The flux component (aligned with d co-ordinate) and the torque component (aligned with the q co-ordinate).This method is based on controlling of stator current by transforming three phase time and speed dependent system into two Co-ordinate dq systems by using equation

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (5)$$

In case of PMSM, d axis current is kept zero as the rotor flux is fixed and determined by magnets[4].

I. DC to AC Converter (Inverter)

A device that converts dc power into ac power at desired output voltage and frequency is called an inverter. Space Vector Pulse Width Modulation, can be said as a scheme, which is a vector approach, used for the controlling of switching states of the power semiconductor switches employed in three phase inverters.

- **Principle of Space vector PWM**

A three-phase mathematical system can be represented by a space vector. Below is given a set of three-phase voltages,
A space vector can be defined by:

$$\boldsymbol{V\,(t) = \frac{3}{2}\,[Va\,(t)ej0\; +\; Vb(t)\frac{ej2\pi}{3}\; +\; Vc\frac{ej4\pi}{3}]} \qquad (6)$$

Where, Va (t), Vb (t), and Vc (t) are three sinusoidal voltages of the same amplitude and frequency but with +120 phase shifts.

The space vector at any given time maintains its magnitude[5]. As time increases, the angle of the space vector increases, causing the vector to rotate with a frequency equal to that of the sinusoidal waveforms.

II. Space Vector Pulse-Width Modulation (SVPWM)

- **Angle and Reference Voltage Vector**

The three-phase output voltage vector is represented by a reference vector that rotates at an angular speed of w = 2pf.a reference voltage vector (Vref) that rotates with angular speed (w) in the ab plane represents three sinusoidal waveforms with angular frequency w in the abc coordinate system.

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Three sinusoidal and balanced voltages are given by the relations:

$$Va(t) = Vref\ cos\ (wt) \quad (7)$$
$$Vb(t) = Vref\ cos\ (wt - 2\pi = 3) \quad (8)$$
$$Vc(t) = Vref\ cos\ (wt + 2\pi = 3) \quad (9)$$

For any three-phase system with three wires and equal load impedances we have

$$Va(t) + Vb(t) + Vc(t) = 0 \quad (10)$$

The three-phase voltages could be described with only two components, a and b, in a two-dimensional plane[6]. The magnitude of each active vector is 2Vdc=3. The active vectors are 6 apart and describe a hexagon boundary.

The locus of the circle projected by the space Reference vector (Vref) depends on V0, V1, V2, V3, V4, V5, V6, and V7.

$$Vref = 2 / 3\ [Va + aVb + a2Vc] \quad (11)$$

Where a = e j2p=3.

The magnitude of the reference vector is

$$|\ Vref\ | = \sqrt{V^2\alpha + V^2\beta} \quad (12)$$

The phase angle is evaluated from Eq.13.

$$\theta = tan - 1\ (V\beta\ /\ V\alpha) \quad (13)$$

When an AC machine is fed by this three-phase voltage a flux which is rotating in nature is being produced in the air gap linking the stator and rotor conductor. This flux can also be shown in voltage form as a vector which also rotates in a different frame known as dq frame.

Clark's Transformation can be used to find the parameters of this rotating vector in the stationary reference frame.

III. Rotating vector in the stationary reference frame

The abc voltages shown are in the three-phase sinusoidal frame which need to be transformed into another two-dimensional dq reference frame as shown in fig.4. This will lead to eight switching states in which six are non-zero and two are zero states.

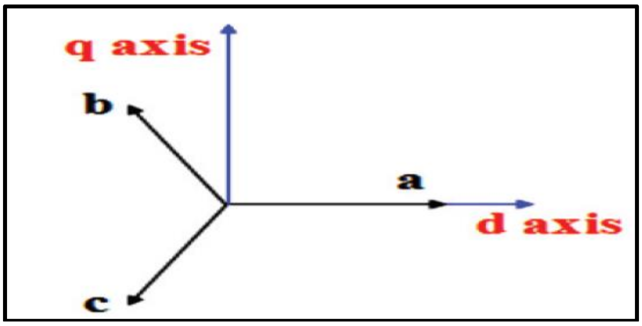

Fig.4 Relation Between abc and Stationary dq reference frame

The abc voltages shown are in the three-phase sinusoidal frame which need to be transformed into another two-dimensional dq reference frame as shown in fig.4. This will lead to eight switching states in which six are non-zero and two are zero states.

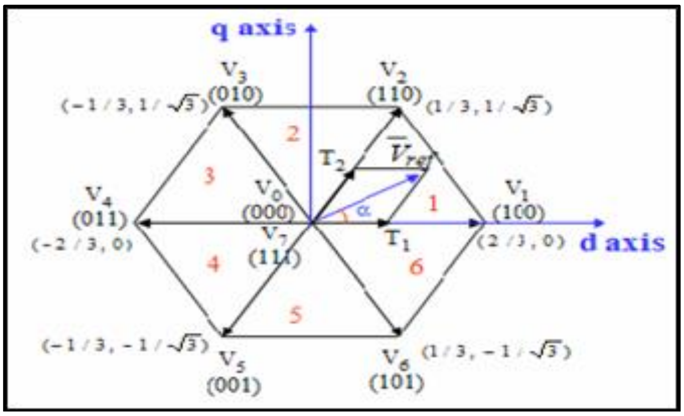

Fig.5: Switching States and Sectors

The six non-zero vectors (V1-V6) lie on the six edges of a hexagon as shown in fig.5.these vectors are displaced by an angular displacement of 60 degrees in space. The rest two states, i.e., zero states which are V0, V7, lie at zero i.e., origin and gives null voltage as an output of the inverter when applied. The aim of SVPWM technique can be understand as to synthesize a vector called reference vector (Vref) by managing the eight available switching patterns.

In the space-vector modulation, a three-phase two-level inverter can be driven to eight switching states where the inverter has six active state (1-6) and two zero state (0 and 7).

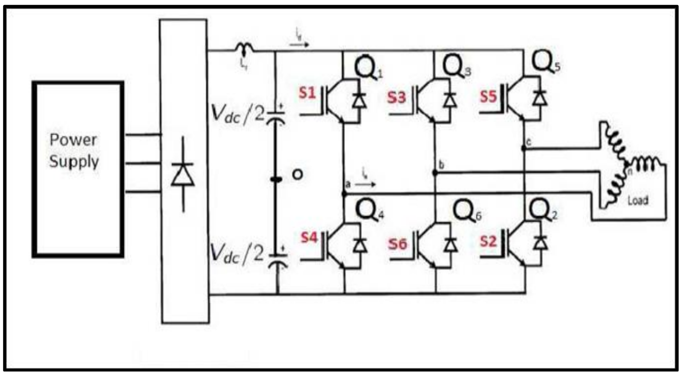

Fig.6. Circuit diagram for two-phase bridge inverter

The pole voltages that can be produced are either Vdc/2 or –Vdc/2. when switches S1, S6, S2 are closed, corresponding pole voltages are Vao = Vdc/2, Vbo = - Vdc/2, and Vco= - Vdc/2. This state is denoted as (1,0,0).Repeating the same procedure, we can find the remaining active non-active states.

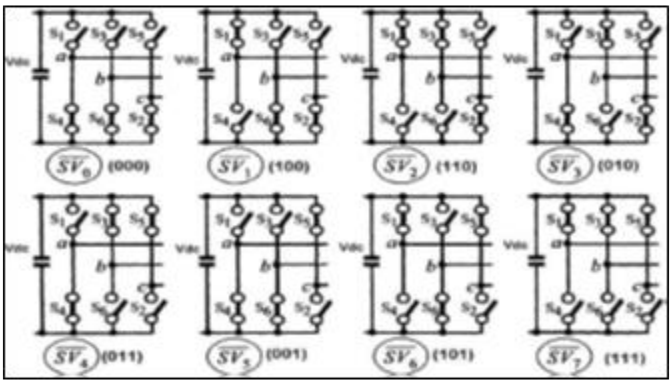

Fig.7. Eight switching states of inverter

Table.1. Summary of Inverter Switching Vectors:

Name	A	B	C	V_{An}	V_{Bn}	V_{Cn}
V_0	0	0	0	0	0	0
V_1	1	0	0	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$
V_2	1	1	0	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$
V_3	0	1	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$
V_4	0	1	1	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$
V_5	0	0	1	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$
V_6	1	0	1	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$
V_7	1	1	1	0	0	0

IV. MATLAB modelling and Simulink

Simulink (Simulation and Link) is an extension of MATLAB by Math Works Inc. It works with MATLAB to offer modelling, simulation, and analysis of dynamical systems under a graphical user interface (GUI) environment. The construction of a model is simplified with click- and- drag mouse operations. Simulink includes a comprehensive block library of toolboxes for both direct and nonlinear analyses[7]. As Simulink is an integral part of MATLAB, it's easy to switch back and forth during the analysis process, and therefore, the user may take full advantage of features offered in both surroundings. Considering the advantages of MATLAB, the proposed algorithm is executed using MATLAB.

5. SIMULINK MODEL OF THE ISG SYSTEM

I. Introduction

The proposed system uses PMSM, which functions as a motor and alternator depending on the speed of the ICE. The motor, It is attached to the shaft of the ICE and also to the battery with the help of the converter, which ensures that the battery is charged up to 48 V as shown in Fig.8.An IC engine is connected to the ISG, and a 48V battery is used to power the loads placed in the hybrid electric vehicle and also to supply power to the ISG when it's operating in motoring mode. This 48-volt system, with the help of a buck converter, charges the 12-volt battery, which is used to power low-voltage loads in HEVs.

The PMSM performs as a motor when the speed of the IC engine is below the 750rpm prescribed minimum cranking speed. Below this speed, an IC engine would be turned off, and a battery would power the engine to achieve a minimum torque. The power electronic converter present helps to convert AC to DC and vice versa with the help of a bidirectional converter. A controller is used to operate the ISG in both generator and motoring mode by sensing the IC engine speed. The control technique used for controlling the system is field-oriented control, which controls the speed and torque of the motor with the help of stator current.

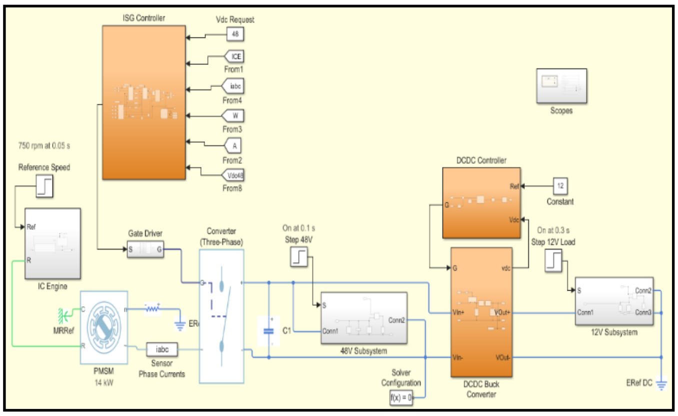

Fig.8.Simulink model for integrated starter Generator (ISG)

A permanent magnet synchronous machine (PMSM) is used as a starter/generator in a simplified 48/12V automotive system as shown a Simulink model in fig.8.The system contains a 48-volt electric network and a 12-volt electric network.

The internal combustion engine is represented by basic mechanical blocks. The PMSM operates as a motor when the speed of the ICE is below the prescribed minimum speed of 750 rpm until the ICE reaches idle speed, at which point it operates as a generator. The PMSM supplies power to the 48V network, the 48V network supplies power to the 12V network.

Table. 2. Parameters of ISG

Parameters	Unit	Values
Maximum Power	Pm	14KW
Maximum Torque	Tm	50Nm
Stator d axis inductance	Ld	0.1mH
Stator q axis inductance	Lq	0.3mH
Stator zero axis inductance	L0	0.05mH
Stator Resistance	Rs	0.005 m ohm
Permanent magnet flux linkage	ψ	0.04Wb
No. of pole pair	P	2

6. SIMULATION RESULTS

A. Engine Starting Operation Mode

When the ICE operates at less than 750 rpm, the ICE switch is turned off, as shown in Fig. 9. And the motor torque supplies positive Q-axis current, as shown in Fig.10 This Q-axis current is known as a torque-controlling component.

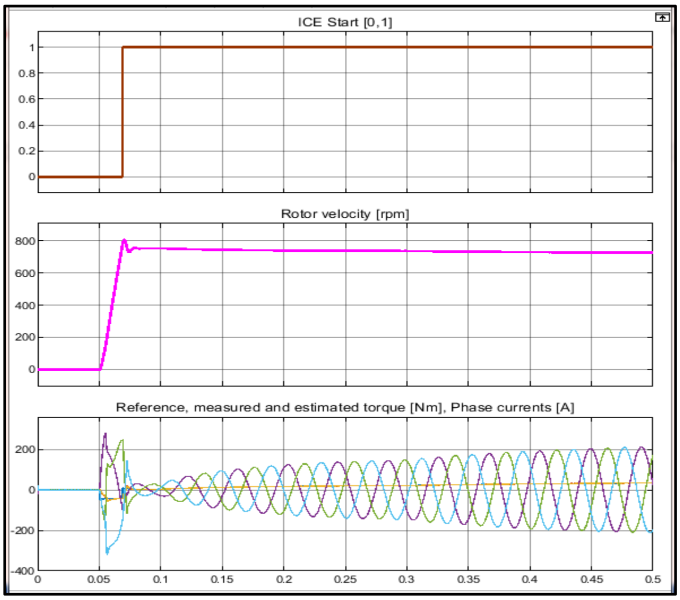

Fig.9. ISG Motoring mode simulation results

The torque supplied is positive in this mode; the maximum torque supplied is 50 Nm. During the starting condition when ICE has not reached its minimum speed, the dc voltage drops because current is flowing out of the battery.

Fig.10. shows the flux component (aligned with d co-ordinate) and the torque component (aligned with the q co-ordinate).

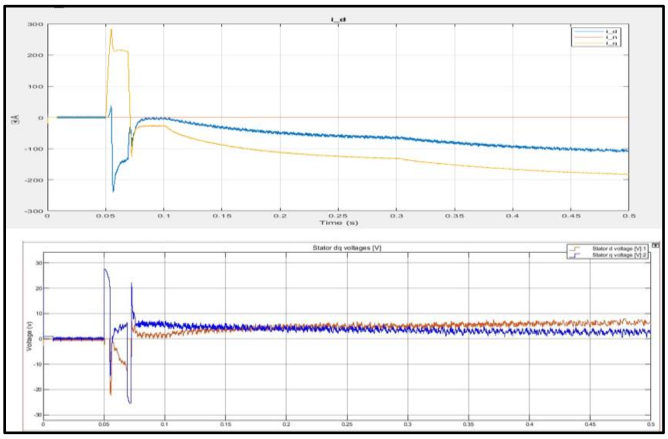

Fig.10. dq-axis current and voltage

B. Alternator Operation Mode

Alternator (generator) mode of operation occurs when ISG reaches over 750 rpm, which is the minimum required speed for an engine to start. Fig.9.shows the graph when the IC engine is turned on. When ICE turns on, ISG operates in alternating mode. The q axis current component is negative in this mode, as shown in Fig.10.likewise Torque supplied is negative, as torque is negative in generator mode.

In generator operation mode, the battery is charged by supplying power to the 48-volt battery from the alternator, as results shown in Fig. 11.

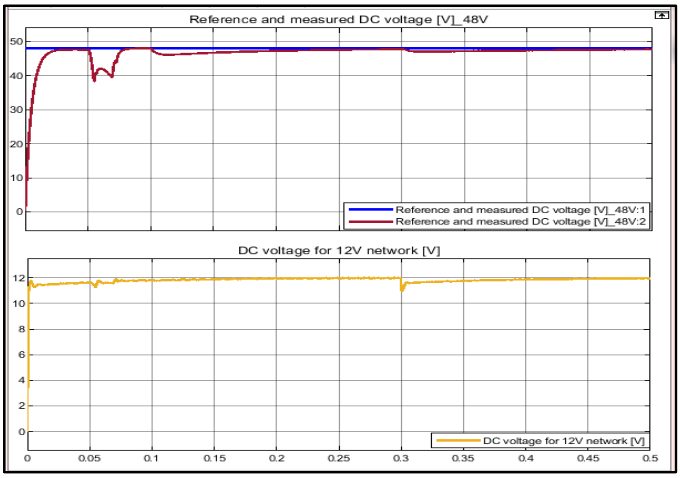

Fig.11. ISG Alternator mode simulation results

In the battery charging mode, the ISG system with a 48- and 12-volt DC power setup is used to charge the battery of the vehicle. The simulation results show that the ISG system is able to charge the battery quickly and efficiently with both 48 and 12 voltage DC power setups.

The system is also able to operate at high efficiency, indicating that it is capable of providing good performance in the battery charging mode.

7. ISG RESULTS COMPARISON WITH CONVENTIONAL STARTING.

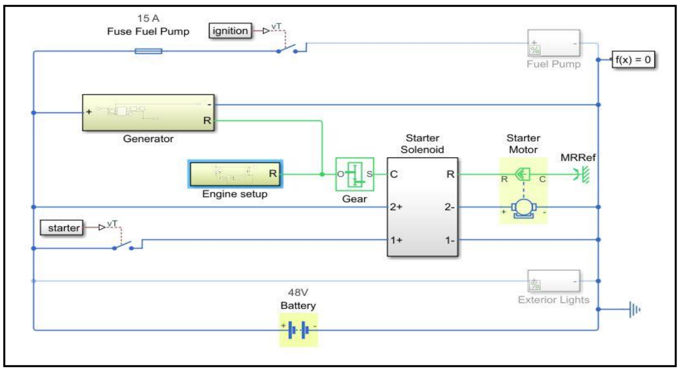

Fig.12.Simulink model for Conventional starting System

- ❑ **Starting Speed**

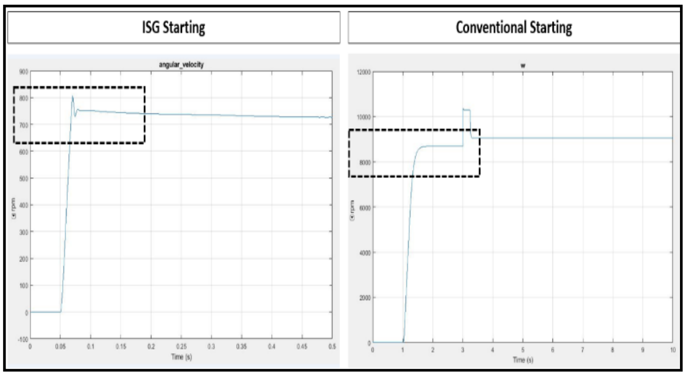

Fig.13 Starting (engine cranking) Speed

- An ISG machine has exactly same speed as it's a flywheel mounted setup, hence as shown in fig.9.ISG having same speed (750 rpm) as per actual Engine cranking speed required.
- A DC Motor has more speed as it is external part mounted on engine to rotate flywheel with mechanical tooth and gears, hence as shown in fig.13. DC starter having different speed (8350 rpm) as per Engine cranking speed required.

❑ **Starting Load Current**

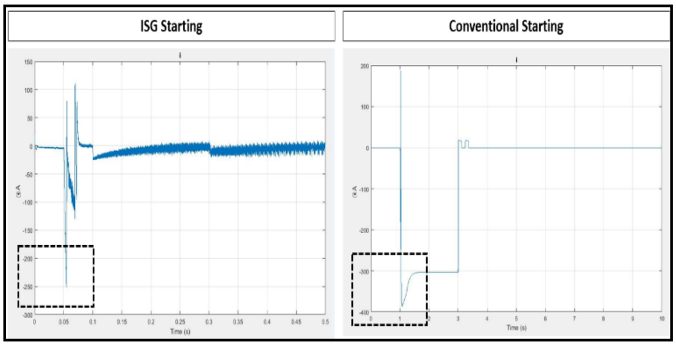

Figure.14 Starting Load Current

- 250 A current is Maximum drawn from 48 V battery with ISG
- 400 A current is Maximum drawn from 48 V battery with separate starter motor

❑ **Starting Power Requirement**

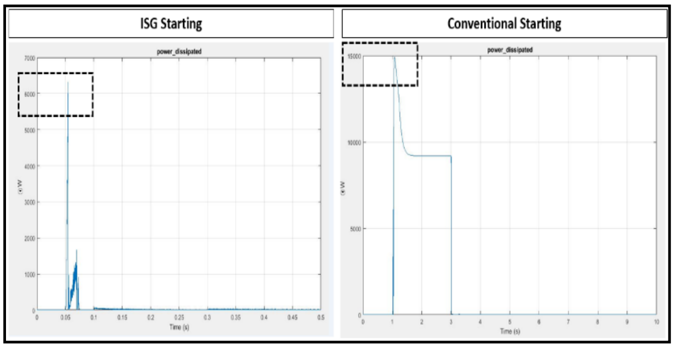

Figure.15 Starting Power Dissipated from Battery

- 6.3 kW power drawn from 48 V battery with ISG
- 14.95 kW power drawn from 48 V battery with separate starter motor

8. CONCLUSION

In this paper, a comprehensive model for an integrated starter generator system has been presented, which can be used for engine starting and battery charging operations in a hybrid electric vehicle. The proposed model was implemented and simulated using the Simulink environment. The simulation results showed that the integrated starter generator system can efficiently start the engine and charge the battery, while maintaining a stable 12V DC voltage output. The system also showed good performance in terms of efficiency, power output, and response time as compared to conventional system.

Overall, the model presented in this paper can be used as a basis for the design and development of integrated starter generator systems for various applications, such as hybrid electric vehicles and micro grids. Further work can be done to refine the model and validate its performance with experimental data. The proposed model can also be extended to include additional features and to explore the potential for energy recovery and efficiency improvement.

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