



International Journal for Innovative Engineering and Management Research

A Peer Reviewed Open Access International Journal

www.ijiemr.org

COPY RIGHT



ELSEVIER
SSRN

2019IJIEMR. Personal use of this material is permitted. Permission from IJIEMR must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. No Reprint should be done to this paper, all copy right is authenticated to Paper Authors

IJIEMR Transactions, online available on 1st Aug 2019. Link

[:http://www.ijiemr.org/downloads.php?vol=Volume-08&issue=ISSUE-08](http://www.ijiemr.org/downloads.php?vol=Volume-08&issue=ISSUE-08)

Title **FUZZY BASED SPEED CONTROL OF SRM DRIVE FOR PV INTEGRATED EV SYSTEM**

Volume 08, Issue 08, Pages: 38–51.

Paper Authors

YANNAM SANDEEP KUMAR, RAVI KUMAR DASARI

Sri Mittapalli College of Engineering, NH-16, Tummalapalem, Guntur (Dt), Andhra Pradesh, India



USE THIS BARCODE TO ACCESS YOUR ONLINE PAPER

To Secure Your Paper As Per **UGC Guidelines** We Are Providing A Electronic Bar Code

FUZZY BASED SPEED CONTROL OF SRM DRIVE FOR PV INTEGRATED EV SYSTEM

¹YANNAM SANDEEP KUMAR, ²RAVI KUMAR DASARI (M.Tech.)

¹M.Tech Student Scholar, Department of Electrical & Electronics Engineering, Sri Mittapalli College of Engineering, NH-16, Tummalapalem, Guntur (Dt), Andhra Pradesh, India.

²Assistant Professor, Department of Electrical & Electronics Engineering, Sri Mittapalli College of Engineering, NH-16, Tummalapalem, Guntur (Dt), Andhra Pradesh, India.

Abstract—This paper presents the use of fuzzy logic control (FLC) for switched reluctance motor (SRM) speed. Switched Reluctance Motors (SRM) has a wide range of industrial applications because of their advantages over conventional AC/DC Drives. This is due to simple construction, ruggedness and inexpensive manufacturing potential. Various methods have used and applied to control SRM speed generally, the PV-fed EV has a similar structure to the hybrid electrical vehicle, whose internal combustion engine (ICE) is replaced by the PV panel. The PV has different characteristics to ICEs, the maximum power point tracking (MPPT) and solar energy utilization are the unique factors for the PV-fed EVs. In order to achieve low cost and flexible energy flow modes, a low cost tri-port converter is proposed in this paper to coordinate the PV panel, SRM and battery. The FLC performs a PI-like control strategy, giving the current reference variation based on speed error and its change. The performance of the drive system was evaluated through MATLAB/SIMULINK software.

Index Terms—Electric vehicles, photo voltaic (PV), power flow control, switched reluctance motors (SRMs), tri-port converter.

1. INTRODUCTION

Photovoltaic Generators (PV) provide a clean and unlimited source of energy. As part of an ongoing project on low-cost PV powered Electrical Vehicles, a control system is evaluated here for a specific configuration, based on PV panels that power a Switched Reluctance Motor, using independent controllers for maximizing the power supply and optimizing the operation of the motor [1-3]. In this paper the Simulink model for the speed control of switched reluctance motor is carried out by using different speed controllers. The Simulink models is designed for P, PI & Fuzzy logic controller separately and their performance result is been compared [4-5]. The

Switched Reluctance Motor is an electric motor which runs by a reluctance torque. For industrial application very high speed of 50,000 rpm motor is used. The speed controllers applied here are based on conventional P& PI Controller and the other one is AI based Fuzzy Logic Controller [6-7]. The PI Controller (proportional integral controller) is a most special case of the PID controller in which the derivative of the error is not being used. Fuzzy logic controller is a most intelligent controller which uses a fuzzy logic to process the input. Fuzzy logic is a many valued logic which is much like a human reasoning. In the industrial control FLC has various applications, particularly where this

conventional control design techniques are very difficult to apply. A comprehensive review has been done for SRM machine modelling, design and simulation and analysis and control [8-10]. Switched Reluctance Motor (SRM) has undergone fast growth in aerospace starter/generator system, hybrid electric vehicles, washing machines, and industrial automation applications over the most recent decades [11]. The main reason behind this is SRM has simple, robust construction and reliable operation. So it can be used as a drive in vibrating and high temperature areas. In addition the cost of the SRM is low and the size of the motor is little and lower weight [12]. However the SRM is a nonlinear motor because it operates in saturation to produce maximum output torque and the developed torque is a nonlinear function of both rotor position and phase current. So it is not advisable to use conventional PID controller to control the speed of switched reluctance motor [13]. Fuzzy logic controller (FLC) one of the intelligent control technique, is used in this work. FLC uses human problem solving methodology to control the speed of non-linear system and the performance of FLC is also good. FLC provides a proper approach for representing, influencing, and executing a human's heuristic knowledge about how to control a system [14]. Application of FLC in control nonlinear, parameter disparity, structure variation and transfer function unknown system shows the suitability of FLC to control the speed of SRM. The simulation was carried out with PID controller and FLC the results obtained are analyzed to test the performance of fuzzy logic controller. The FLC based speed control technique for SRM shows better performance [15].

II. Topology and Operational Modes

A. Proposed topology and working modes

The proposed Tri-port topology has three energy terminals, PV, battery and SRM. They are linked by a power converter which consists of four switching devices ($S_0 \sim S_3$), four diodes ($D_0 \sim D_3$) and two relays, as shown in Fig.1. [10]. By controlling relays J1 and J2, the six operation modes are supported, as shown in Fig. 3; the corresponding relay actions are illustrated in Table I. In mode 1, PV is the energy source to drive the SRM and to charge the battery. In mode 2, the PV and battery are both the energy sources to drive the SRM. In mode 3, the PV is the source and the battery is idle. In mode 4, the battery is the driving source and the PV is idle. In mode 5, the battery is charged by a single-phase grid while both the PV and SRM are idle. In mode 6, the battery is charged by the PV and the SRM is idle.

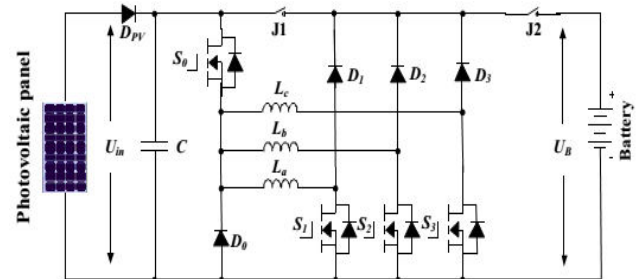


Fig.1. the proposed Tri-port topology for PV-powered SRM drive.

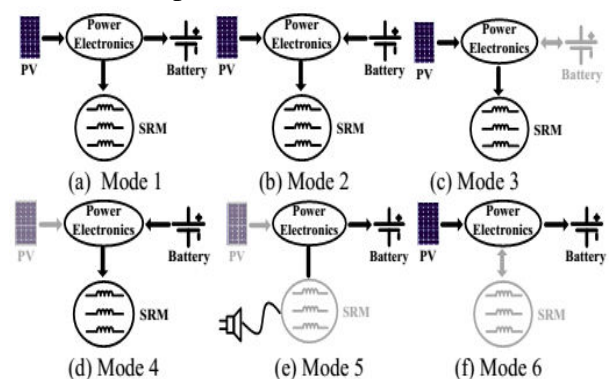


Fig.2. Six operation modes of the proposed Tri-port topology.

TABLE 1. J1 and J2 Actions under Different Modes

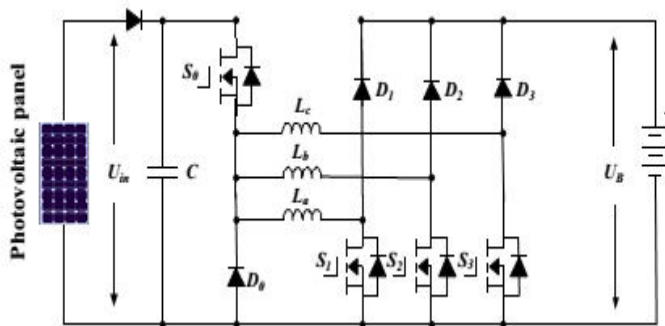
Mode	J1 and J2
1	J1 turn-off; J2 turn-on
2	J1 and J2 turn-on
3	J1 turn-on; J2 turn-off
4	J1 and J2 turn-on
5	J1 and J2 turn-on
6	J1 turn-off; J2 turn-on

B. Driving modes

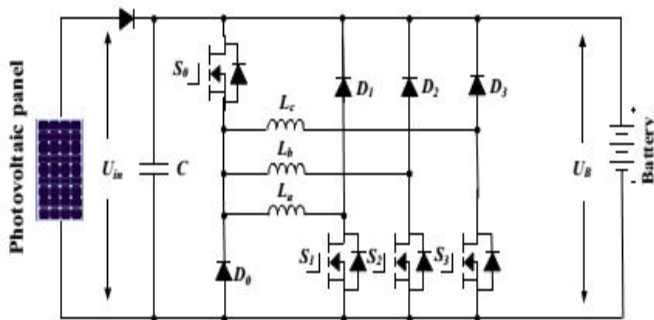
Operating modes 1~4 are the driving modes to provide traction drive to the vehicle.

(1) Mode 1

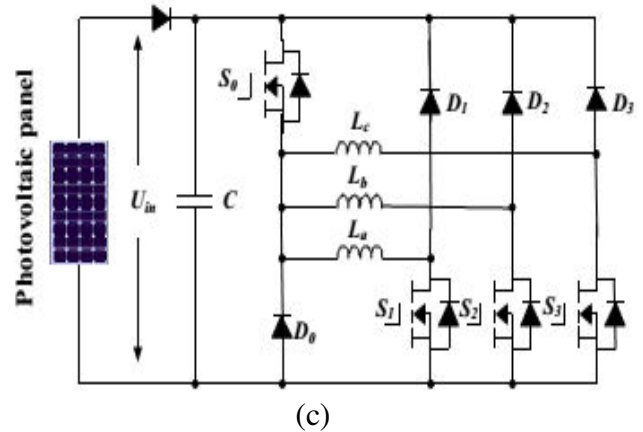
At light loads of operation, the energy generated from the PV is more than the SRM needed; the system operates in mode 1. The corresponding operation circuit is shown in Fig.3 (a), in which relay J1 turns off and relay J2 turns on. The PV panel energy feed the energy to SRM and charge the battery; so in this mode, the battery is charged in EV operation condition.



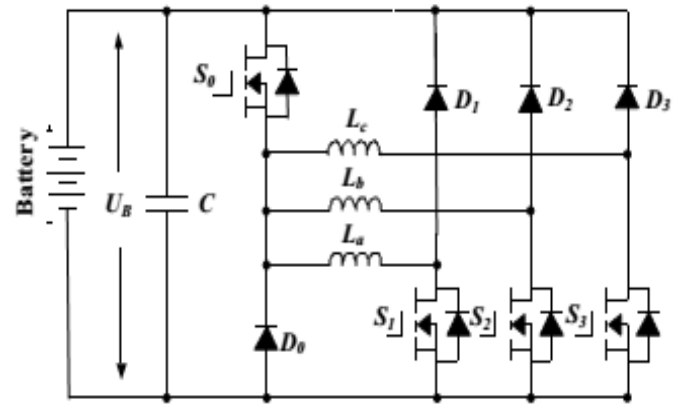
(a).Operation circuit under mode 1



(b)



(c)



(d).Operation circuit under mode 4

Fig.3.The equivalent circuits under driving modes.

(2) Mode 2

When the SRM operates in heavy load such as uphill driving or acceleration, both the PV panel and battery supply power to the SRM. The corresponding operation circuit is shown in Fig. 3(b), in which relay J1 and J2 are turned on.

(3) Mode 3

When the battery is out of power, the PV panel is the only energy source to drive the vehicle. The corresponding circuit is shown in Fig. 3(c). J1 turns on and J2 turns off.

(4) Mode 4

When the PV cannot generate electricity due to low solar irradiation, the battery supplies power to the SRM. The corresponding topology is illustrated in Fig. 3(d). In this mode, relay J1 and J2 are both conducting.

C. Battery charging modes

Operating modes 5 and 6 are the battery charging modes.

(5) Mode 5

When PV cannot generate electricity, an external power source is needed to charge the battery, such as AC grid. The corresponding circuit is shown in Fig. 4(a). J1 and J2 turns on. Point A is central tapped of phase windings that can be easily achieved without changing the motor structure. One of the three phase windings is split and its midpoint is pulled out, as shown in Fig. 4(a). Phase windings La1 and La2 are employed as input filter inductors. These inductors are part of the drive circuit to form an AC-DC rectifier for grid charging.

(6) Mode 6

When the EV is parked under the sun, the PV can charge the battery. J1 turns off; J2 turns on. The corresponding charging circuit is shown in Fig.4 (b).

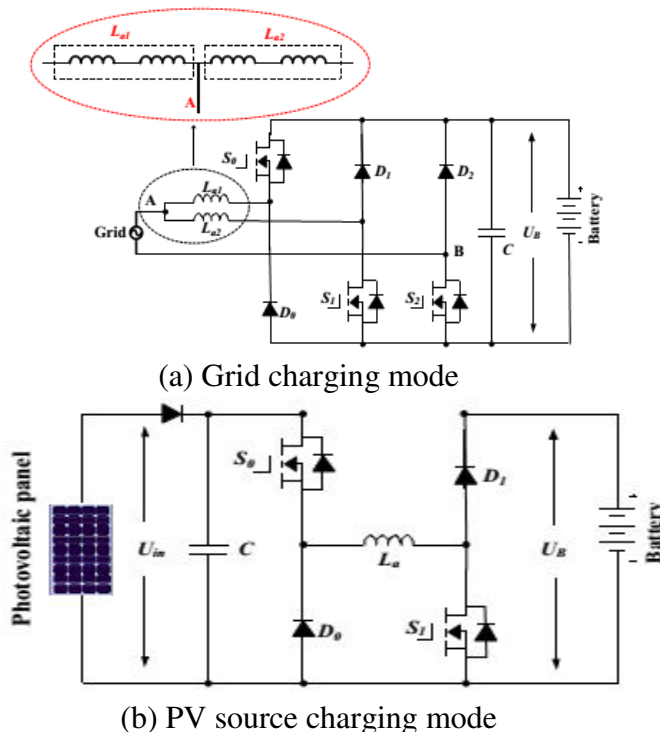


Fig.4 Equivalent circuits of charging condition modes

III. Control Strategy under Different Modes

In order to make the best use of solar energy for driving the EV, a control strategy under different modes is designed.

A. Single source driving mode

According to the difference in the power sources, there are PV-driving; battery-driving and PV and battery parallel fed source. In a heavy load condition, the PV power cannot support the EV, mode 2 can be adopted to support enough energy and make full use of solar energy. Fig. 5(a) shows the equivalent power source; the corresponding PV panel working points is illustrated in Fig.5 (b). Because the PV is paralleled with the battery, the PV panel voltage is clamped to the battery voltage U_B . In mode 2, there are three working states: winding excitation, energy recycling and freewheeling states, as shown in Fig.6. Modes 3 and 4 have similar working states to mode 2. The difference is that the PV is the only source in mode 3 while the battery is the only source in mode 4.

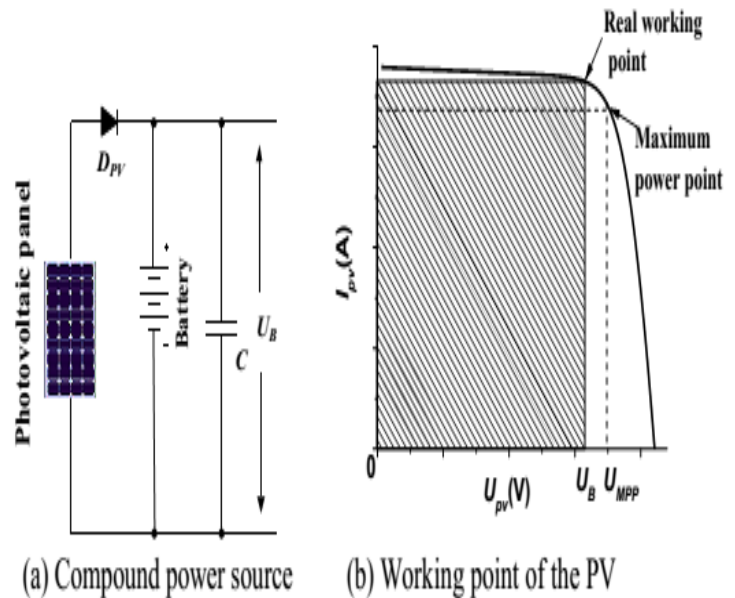


Fig.5. Power supply at mode 2

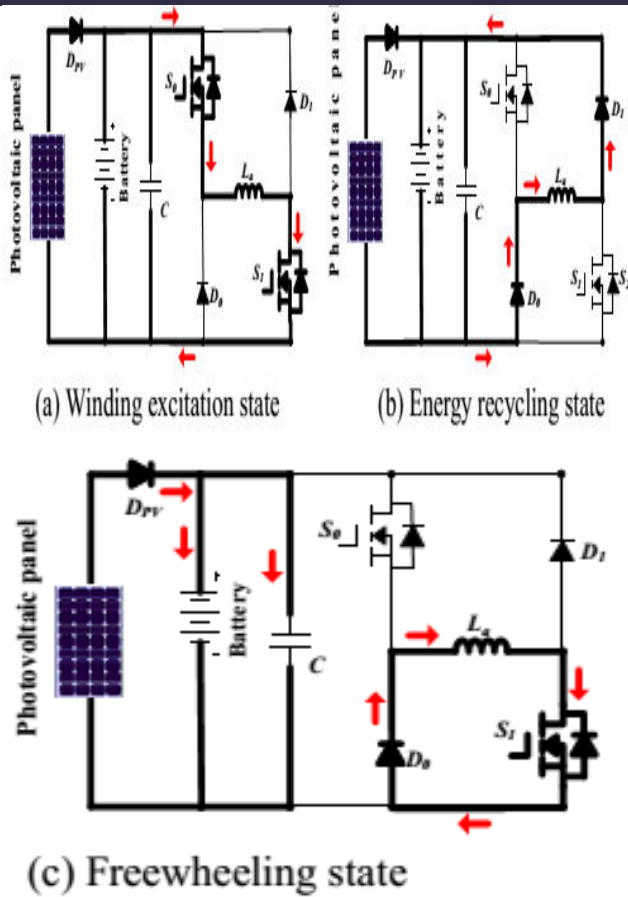


Fig.6. Working states at mode 2

Neglecting the voltage drop across the power switches and diodes, the phase voltage is given by

$$\begin{aligned}
 U_{in} &= R_k i_k + \frac{d\psi(i_k, \theta_r)}{dt} \\
 &= R_k i_k + L_k \frac{di_k}{dt} + i_k \omega_r \frac{dL_k}{d\theta_r}, \quad k = a, b, c
 \end{aligned} \quad (1)$$

where U_{in} is the DC-link voltage, k is phase a , b , or c , R_k is the phase resistance, i_k is the phase current, L_k is the phase inductance, θ_r is the rotor position, $\psi(i_k, \theta_r)$ is the phase flux linkage depending on the phase current and rotor position, and ω_r is the angular speed. The third term in Eq.1 is the back electromotive force (EMF) voltage given by

$$e_k = i_k \omega_r \frac{dL_k}{d\theta_r} \quad (2)$$

Hence, the phase voltage is found by

$$U_k = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (3)$$

In the excitation region, turning on S_0 and S_1 will induce a current in phase a winding, as show in Fig.6 (a). Phase a winding is subjected to the positive DC bus voltage.

$$+U_{in} = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (4)$$

When S_0 is off and S_1 is on, the phase current is in a freewheeling state in a zero voltage loop, as shown in Fig.6(c), the phase voltage is zero.

$$0 = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (5)$$

In the demagnetization region, S_0 and S_1 are both turned off, and the phase current will flow back to the power supply, as show in Fig.6 (b). In this state, the phase winding is subjected to the negative DC bus voltage, and the phase voltage is

$$-U_{in} = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (6)$$

In single source driving mode, the voltage-PWM control is employed as the basic scheme, as illustrated in Fig.7. According to the given speed ω^* , the voltage-PWM control is activated at speed control.

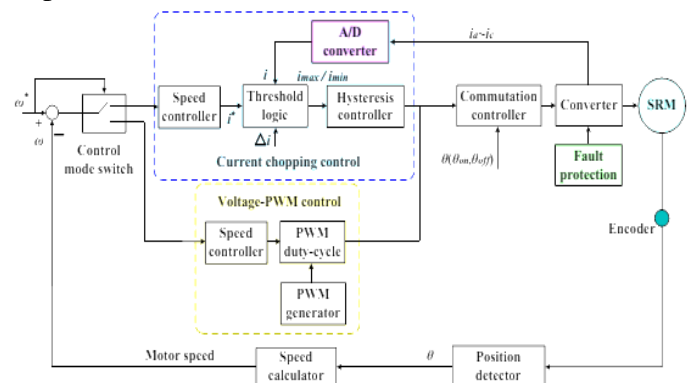


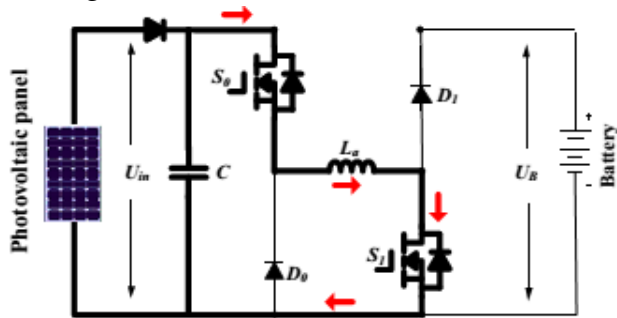
Fig 7. SRM control strategy under single source driving mode.

B. Driving-charging hybrid control strategy

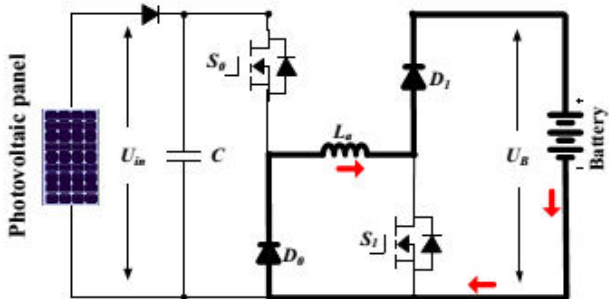
In the driving-charging hybrid control, the PV is the driving source and the battery is charged by the freewheeling current, as illustrated in drive mode 1. There are two control objectives: maximum power point tracking (MPPT) of the PV panel and speed control of the SRM.

The dual-source condition is switched from a PV-driving mode. Firstly, the motor speed is controlled at a given speed in mode 3. Then, J2 is tuned on and J1 is off to switch to mode 1. By controlling the turn-off angle, the maximum power of PV panel can be tracked.

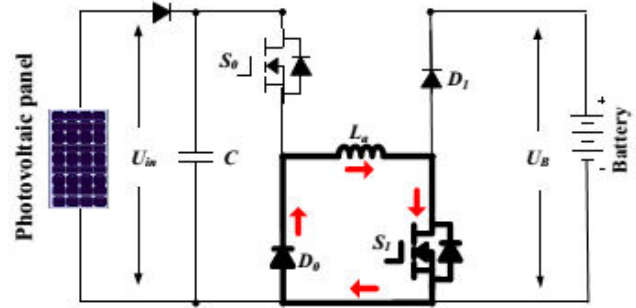
There are three steady working states for the dual-source mode (mode 1), as shown in Fig.8. In Fig. 8(a), S0 and S1 conduct, the PV panel charges the SRM winding to drive the motor; In Fig. 8(b), S0 and S1 turn off; and the battery is charged with freewheeling current of the phase winding.



(a) Winding exciting state



(b) Battery charging state



(c) Freewheeling state

Fig.8 Mode 1 working states

Fig.9 is the control strategy under driving-charging mode. In Fig.9, θ_{on} is the turn on angle of SRM; θ_{off} is the turn-off angle of SRM. By adjusting turn-on angle, the speed of SRM can be controlled; the maximum power point tracking of PV panel can be achieved by adjusting turn-off angle, which can control the charging current to the battery.

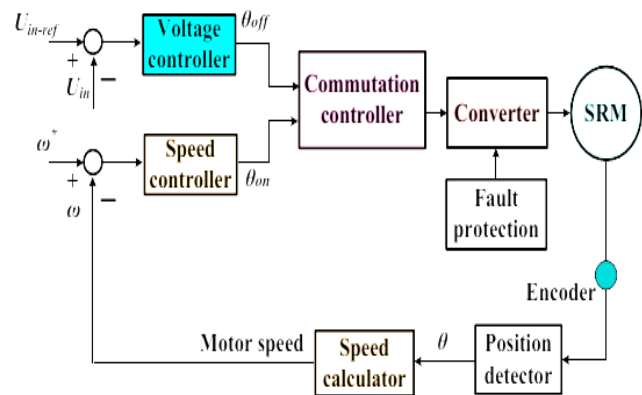


Fig.9. Control strategy under driving-charging mode (mode 1)

C. Grid-charging control strategy

The proposed topology also supports the single-phase grid charging. There are four basic charging states and S0 is always turned off. When the grid instantaneous voltage is over zero, the two working states are presented in Fig.10 (a) and (b). In Fig.10 (a), S1 and S2 conduct, the grid voltage charges the phase winding L_{a2} , the corresponding equation can be expressed as Eq.7; In Fig.10.(b), S1 turns off and S2 conducts, the grid is connected in series

with phase winding to charges the battery, the corresponding equation can be expressed as Eq.8.

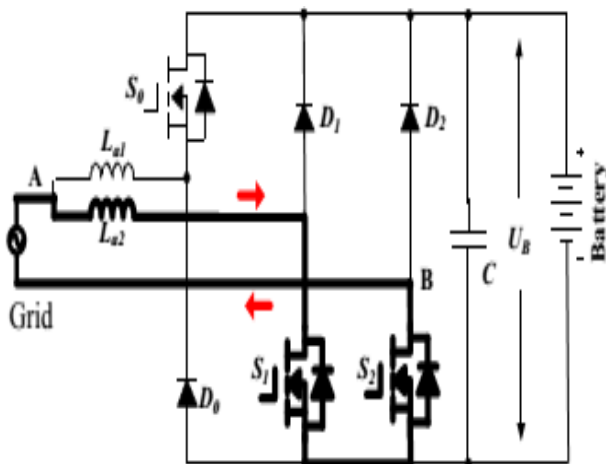
$$U_{grid} = L_{a2} \cdot \frac{di_{grid}}{dt} \quad (7)$$

$$U_B - U_{grid} = L_{a2} \cdot \frac{di_{grid}}{dt} \quad (8)$$

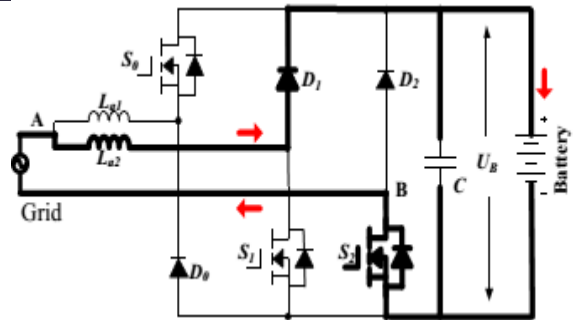
When the grid instantaneous voltage is below zero, the two working states are presented in Fig. 10(c) and (d). In Fig.10.(c), S1 and S2 conduct, the grid voltage charges the phase winding La1 and La2, the corresponding equation can be expressed as Eq. (9); In Fig.10(d), S1 keeps conducting and S2 turns off, the grid is connected in series with phase winding La1 and La2 to charges the battery, the corresponding equation can be expressed as Eq.10.

$$U_{grid} = \frac{L_{a1} + L_{a2}}{L_{a1} \cdot L_{a2}} \cdot \frac{di_{grid}}{dt} \quad (9)$$

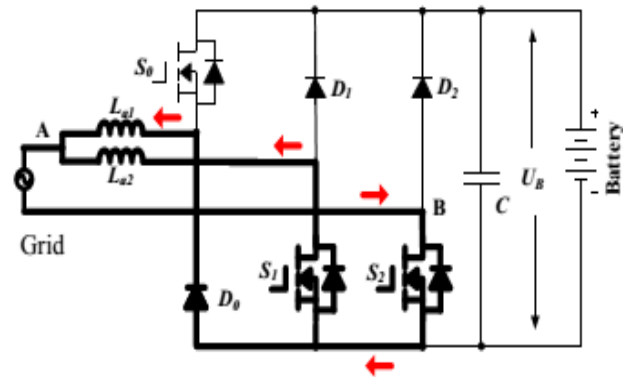
$$-U_B - U_{grid} = \frac{L_{a1} + L_{a2}}{L_{a1} \cdot L_{a2}} \cdot \frac{di_{grid}}{dt} \quad (10)$$



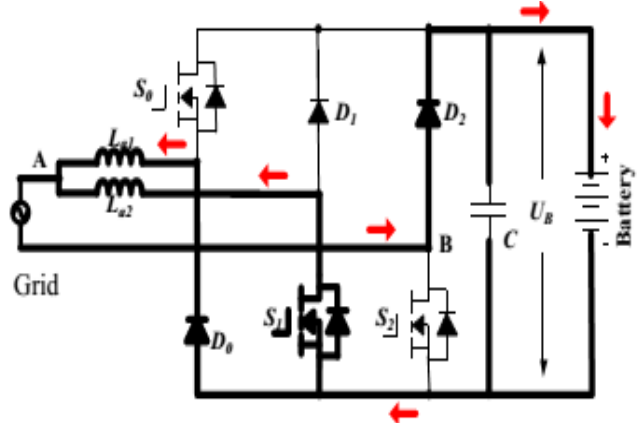
(a) Grid charging state 1 ($U_{grid} > 0$)



(b) Grid charging state 2 ($U_{grid} > 0$)



(c) Grid charging state 3 ($U_{grid} < 0$)



(d) Grid charging state 4 ($U_{grid} < 0$)

Fig.10. Mode 5 charging states

In Fig.11. U_{grid} is the grid voltage; by the phase lock loop (PLL), the phase information can be got; I_{ref_grid} is the given amplitude of the grid current. Combining $\sin\theta$ and I_{ref_grid} , the instantaneous grid current reference i_{ref_grid} can be calculated. In this mode, when $U_{grid} > 0$, the inductance is L_{a2} ; when $U_{grid} < 0$, the inductance is paralleled L_{a1} and L_{a2} ; in order to adopt the change in the

inductance, hysteresis control is employed to realize grid current regulation. Furthermore, hysteresis control has excellent loop performance, global stability and small phase lag that makes grid connected control stable.

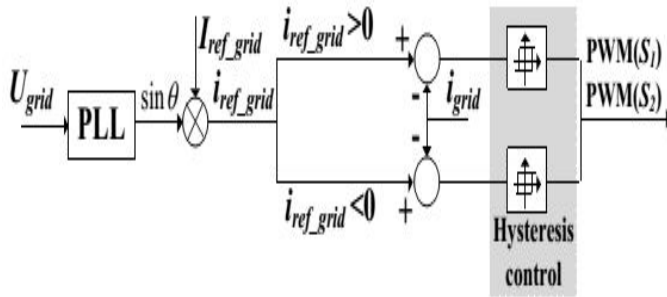
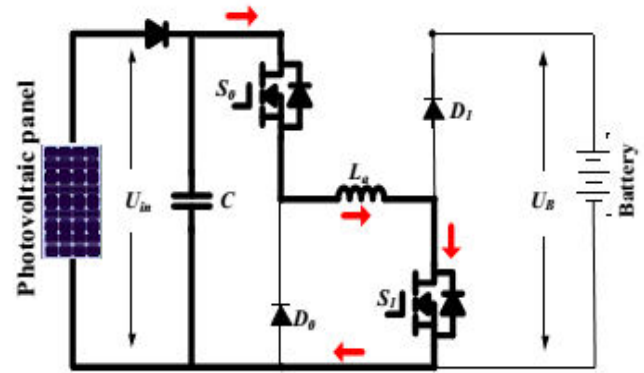


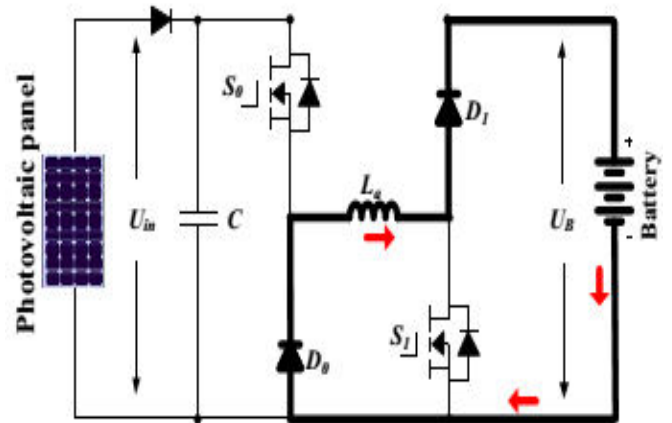
Fig.11. Grid-connected charging control (Mode 5).

D. PV-fed charging control strategy

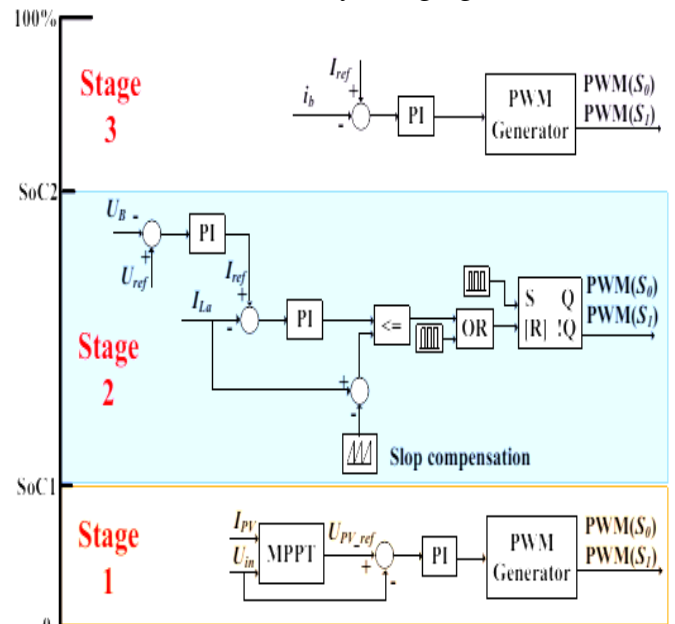
In this mode, the PV panel charges the battery directly by the driving topology. The phase windings are employed as inductor; and the driving topology can be functioned as interleaved Buck boost charging topology. For one phase, there are two states, as shown in Fig. 12(a) and (b). When S0 and S1 turn on, the PV panel charges phase inductance; when S0 and S1 turns off, the phase inductance discharges energy to battery. According to the state-of-charging (SoC), there are three stages to make full use of solar energy and maintain battery healthy condition, as illustrated in Fig.12 (c). During stage 1, the corresponding battery SoC is in 0~SoC1, the battery is in extremely lack energy condition, the MPPT control strategy is employed to make full use of solar energy. During stage 2, the corresponding battery SoC is in SoC1~ SoC2, the constant voltage control is adapted to charging the battery. During stage 3, the corresponding battery SoC is in SoC2~1, the micro current charging is adapted. In order to simplify the control strategy, constant voltage is employed in PV panel MPPT control.



(a) Phase inductance charging



(b) Battery charging



(c) Charging control strategy.

Fig.12 Mode 6 charging states and control strategy.

VII. DESIGN OF A FUZZY CONTROLLER

The trouble with respect to the PI controller gain is the adjusting of the controller in order to accomplish the ideal activity of the undertaking. The significant disadvantage of the PI controller is confronted when the procedure is nonlinear and furthermore when the framework is having motions. Thinking about every one of these actualities, a fluffy rationale controller was actualized. A fluffy controller can work in direct and additionally in nonlinear structure parameters. Fluffy Logic requires some numerical parameters with the end goal to work, for example, what is viewed as huge mistake and huge rate-of-progress of blunder, yet correct estimations of these numbers are normally not basic except if extremely responsive execution is required in which case experimental tuning would decide them.

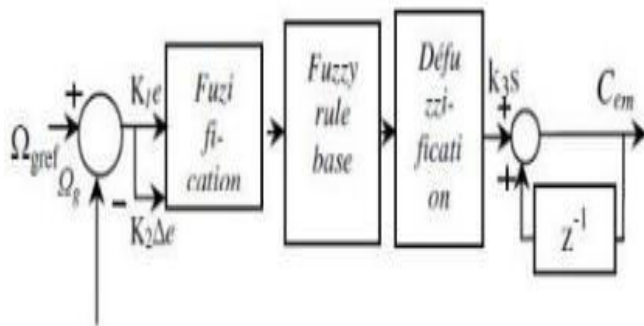


Fig.13 Fuzzy Logic Controller

FL requires some numerical parameters with the end goal to work, for example, what is viewed as noteworthy mistake and huge rate-of-progress of-blunder, yet correct estimations of these numbers are normally not basic except if extremely responsive execution is required in which case exact tuning would decide them. For instance, a temperature control framework could utilize a solitary temperature criticism sensor whose information is subtracted from the

direction flag to process "blunder" and after that time-separated to yield the mistake incline or rate-of-progress of-blunder, in the future called "blunder dab".

MATLAB/SIMULATION RESULTS

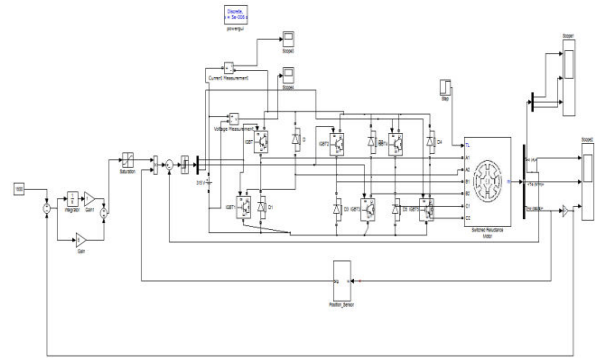
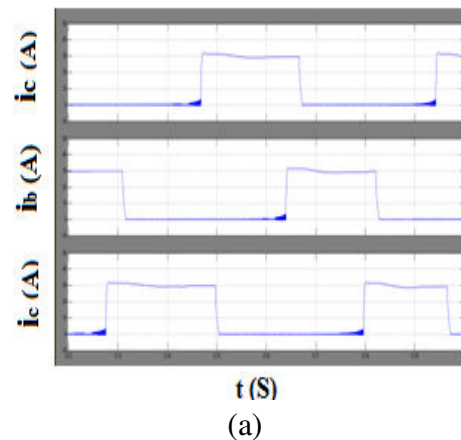
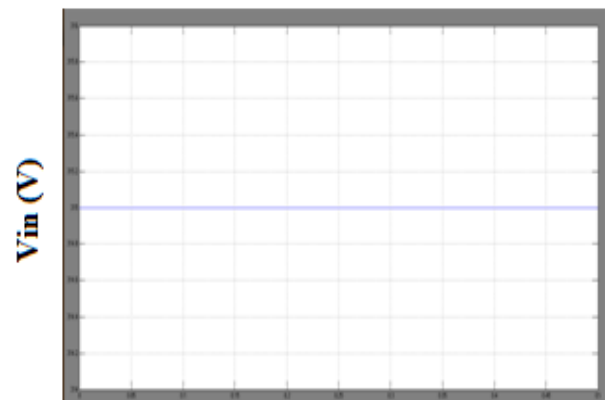


Fig.14 Matlab/simulink circuit for SRM drive model diagram



(a)



(b)

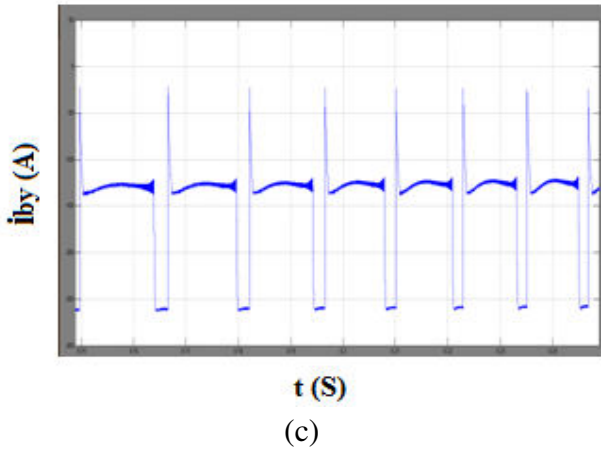


Fig 15 Simulation results of driving-charging mode (mode 1)

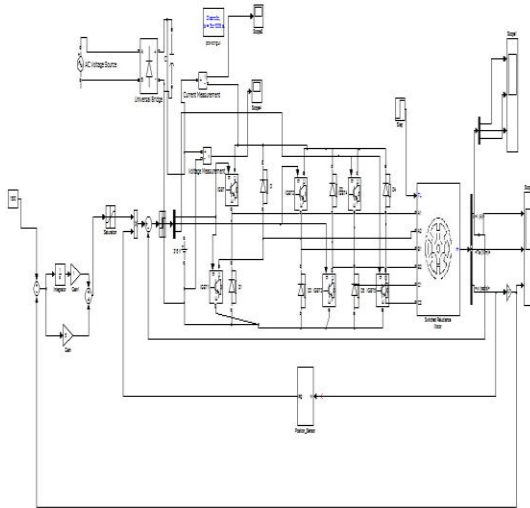
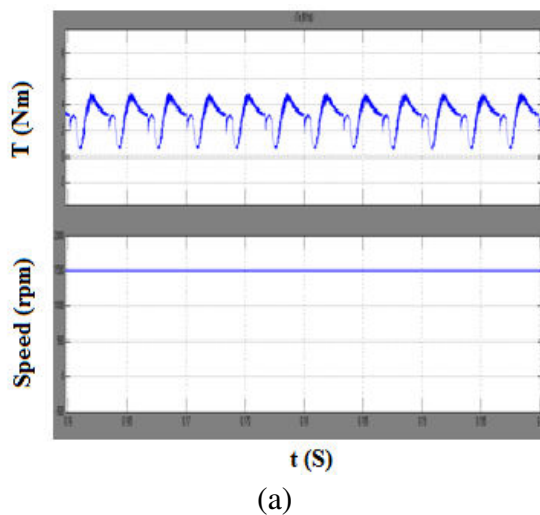
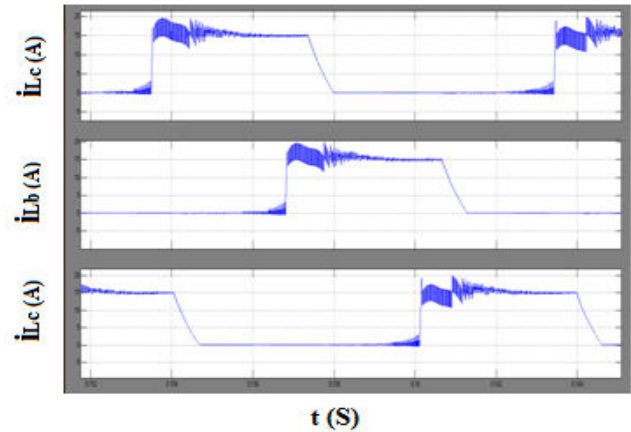


Fig.16 Matlab/simulinkcircuit for SRM drive model diagram



(a)



(b) Simulation results of single source driving mode (modes 3 and 4)

Fig.17 Simulation results for driving conditions at modes 1, 3 and 4.

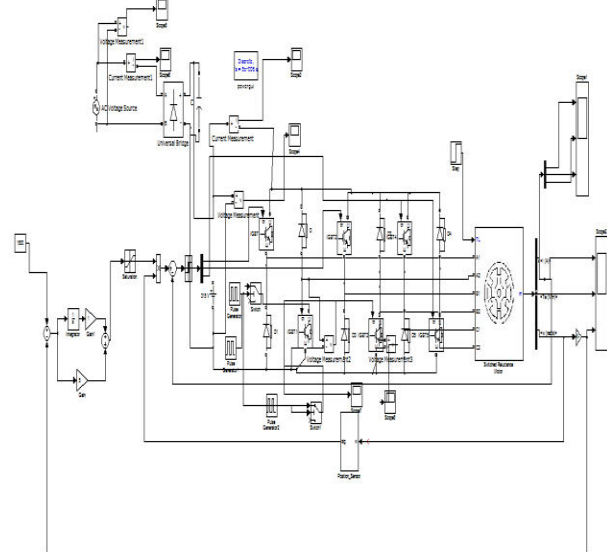
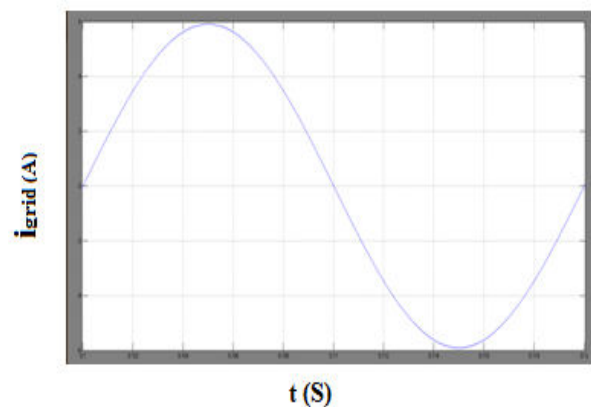


Fig.18 Matlab/simulinkcircuit for SRM drive model diagram



t (S)

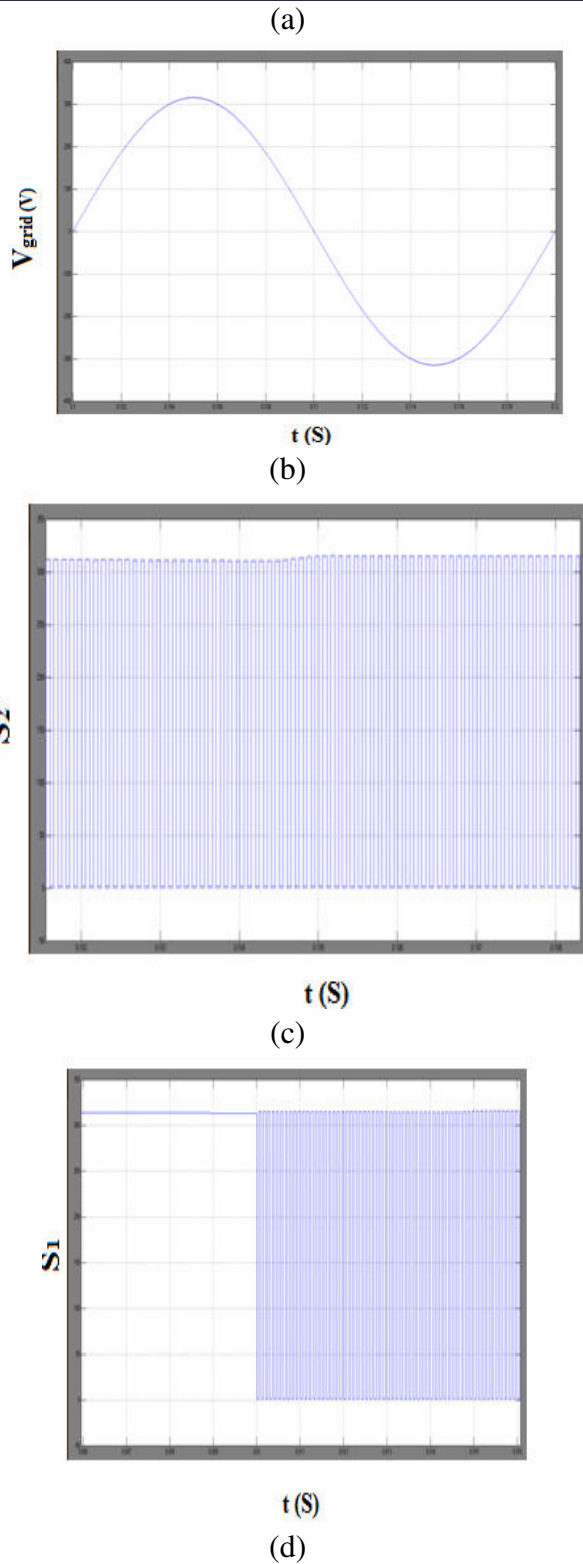


Fig.19. Grid charging (mode 5)

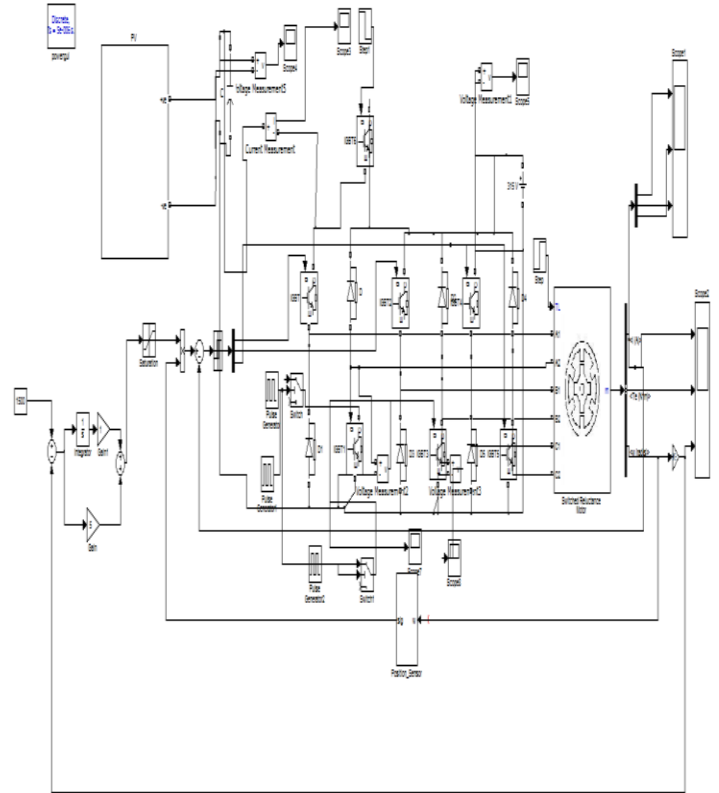
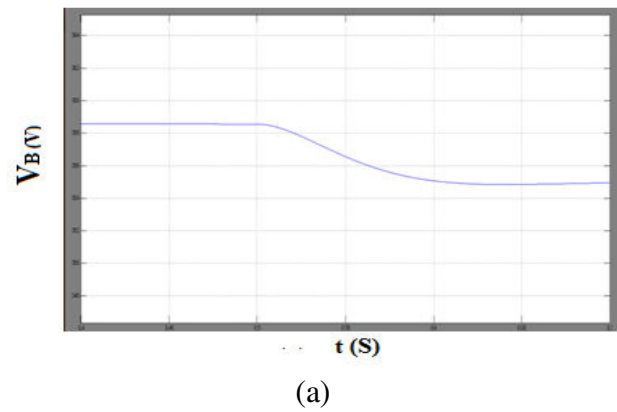
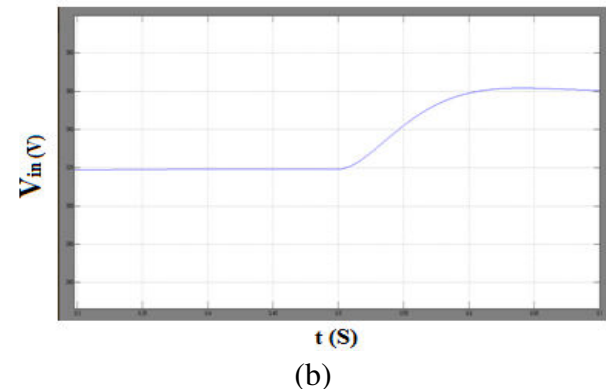


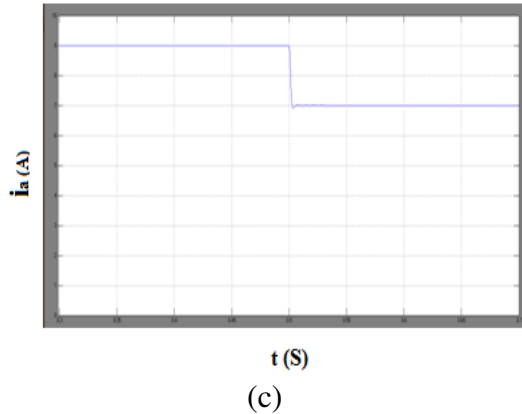
Fig.20 Matlab/simulink circuit for PV-powered SRM drive model diagram



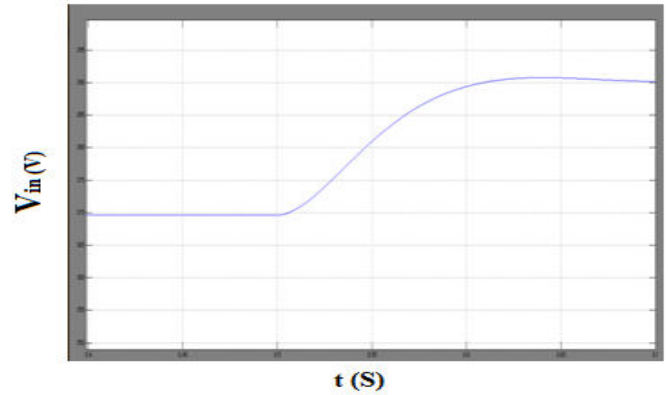
(a)



(b)



(c)



(b)

Fig.21 PV charging mode 6 (stage 1 to stage 2)

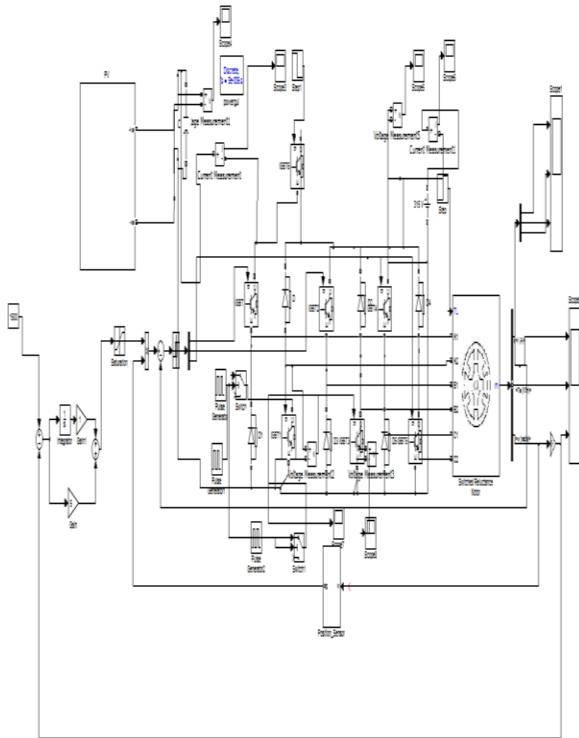
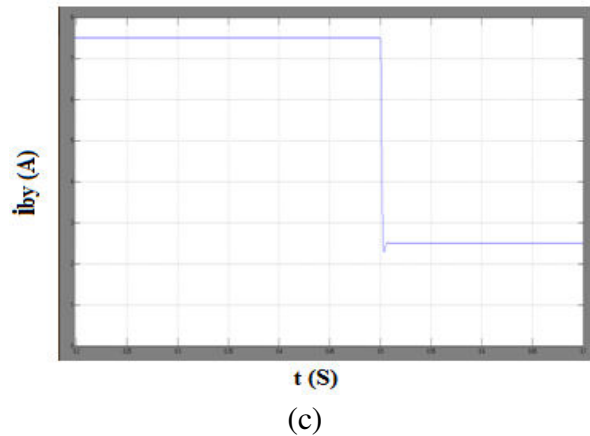
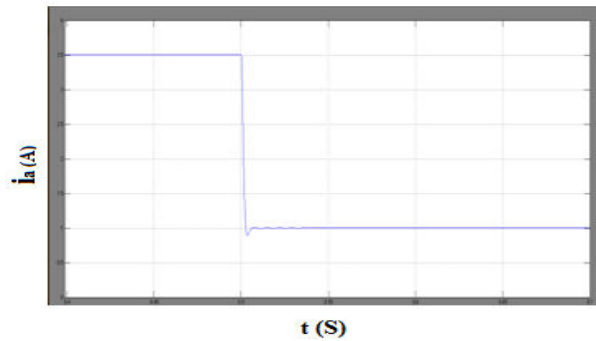


Fig.22 Matlab/simulink circuit for PV-powered SRM drive model diagram

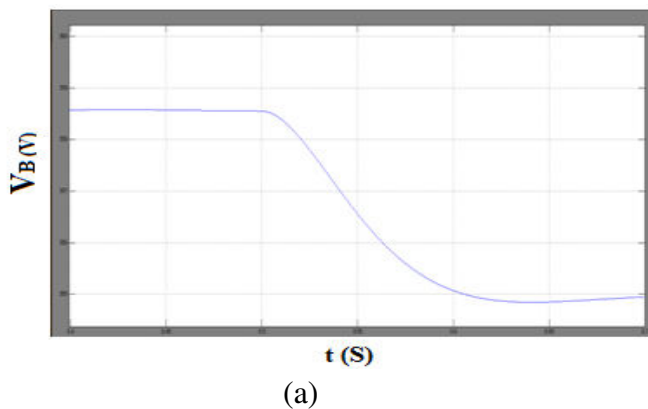


(c)



(a) PV charging mode 6 (stage 2 to stage 3)

Fig.23 Simulation results for charging modes.



(a)

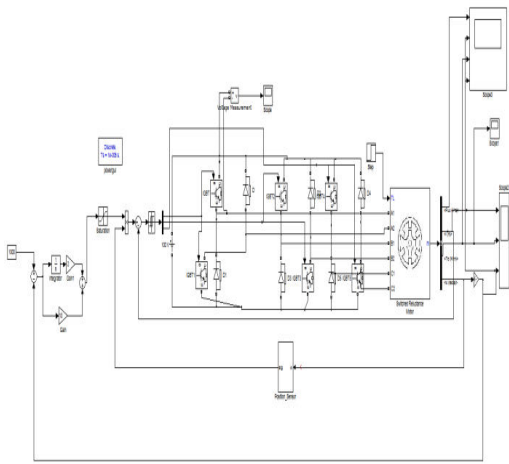


Fig.24 Matlab/simulink circuit for SRM drive model diagram With PI controller

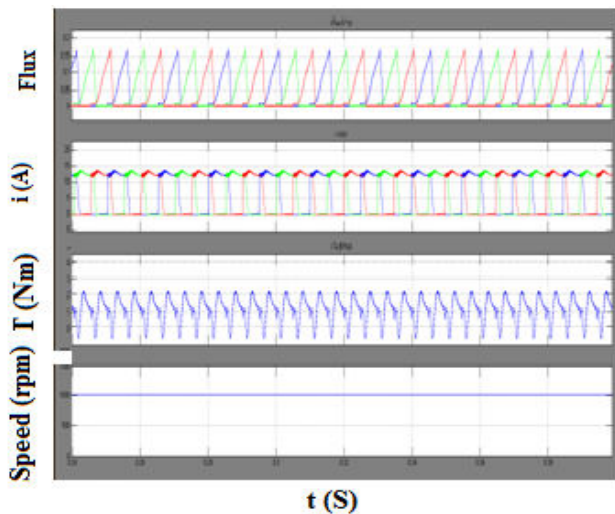


Fig.25 Flux, Current, Speed and Torque

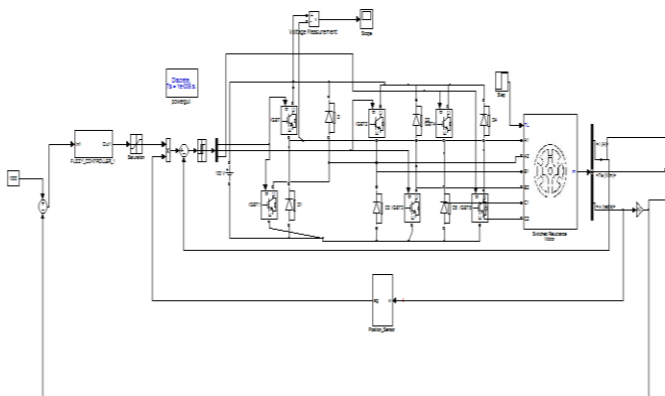


Fig.26 Matlab/simulink circuit for SRM drive model diagram With Fuzzy controller

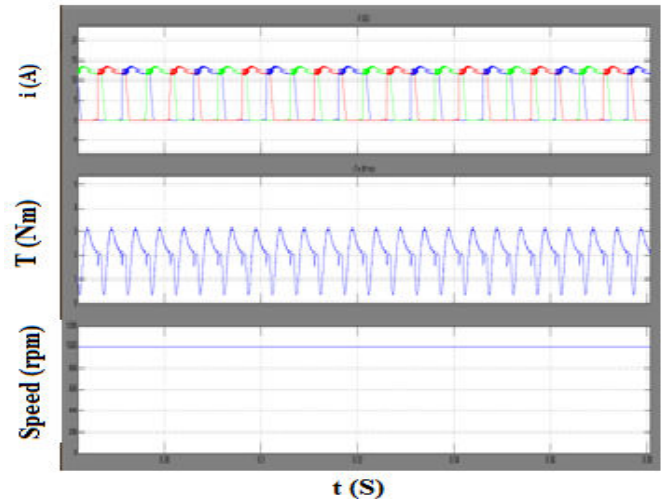


Fig.27 Current, Speed and Torque of SRM

CONCLUSION

Since PV-fed EVs are a greener and more sustainable technology than conventional ICE vehicles, this work will provide a feasible solution to reducing the total costs and CO2 emissions of electrified vehicles. Furthermore, the proposed technology may also be applied to similar applications such as fuel cell powered EVs. Fuel cells have a much higher power density and are thus better suited for EV applications. In this work the SRM dynamic performance is implemented by using MATLAB/Simulink. In conventional methods the speed control of SRM motor is concluded by P, PI. Here it is executed with Fuzzy Logic Controller. Fuzzy Logic Controller gives the required output than the other controllers. In this proposed method the fuzzy logic controller ensure excellent reference tracking of switched reluctance motor drives. This fuzzy logic controller gives the best speed tracking without overshoot and enhances the speed regulation.

REFERENCES

[1] A. Emadi, L. Young-Joo, K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric

vehicles,” IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2237-2245, Jun. 2008.

[2] B. I. K. Bose, “Global energy scenario and impact of power electronics in 21st century,” IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2638-2651, Jul. 2013.

[3] J. de Santiago, H. Bernhoff, B. Ekergård, S. Eriksson, S. Ferhatovic, R. Waters, and M. Leijon, “Electrical motor drivelines in commercial allelectric vehicles: a review,” IEEE Trans. Veh. Technol., vol. 61, no. 2, pp. 475-484, Feb. 2012.

[4] Z. Amjadi, S. S. Williamson, “Power-electronics-based solutions for plugin hybrid electric vehicle energy storage and management systems,” IEEE Trans. Ind. Electron., vol. 57, no. 2, pp. 608-616, Feb. 2010.

[5] A. Kuperman, U. Levy, J. Goren, A. Zafransky, and A. Savernin, “Battery charger for electric vehicle traction battery switch station,” IEEE Trans. Ind. Electron., vol. 60, no. 12, pp. 5391-5399, Dec. 2013.

[6] S. G. Li, S. M. Sharkh, F. C. Walsh, and C. N. Zhang, “Energy and battery management of a plug-in series hybrid electric vehicle using fuzzy logic,” IEEE Trans. Veh. Technol., vol. 60, no. 8, pp. 3571-3585, Oct. 2011.

[7] C. H. Kim, M. Y. Kim, and G. W. Moon, “A modularized charge equalizer using a battery monitoring IC for series-connected Li-Ion battery Strings in electric vehicles,” IEEE Trans. Power Electron., vol. 28, no. 8, pp. 3779-3787, May 2013.

[8] Z. Ping, Z. Jing, L. Ranran, T. Chengde, W. Qian, “Magnetic characteristics investigation of an axial-axial flux compound-structure PMSM used for HEVs,” IEEE Trans. Magnetics, vol. 46, no. 6, pp. 2191- 2194, Jun. 2010.

[9] A. Kolli, O. Béthoux, A. De Bernardinis, E. Labouré, and G. Coquery, “Space-vector PWM

control synthesis for an H-bridge drive in electric vehicles,” IEEE Trans. Veh. Technol., vol.62, no.6, pp. 2441-2452, Jul. 2013.

[10] http://www.bluebird-electric.net/blueplanet_ecostar/solar_assisted_electric_vehicles_sustainable_transport_cars_vans.htm

[11] S. M. Yang, and J. Y. Chen, “Controlled dynamic braking for switched reluctance motor drives with a rectifier front end,” IEEE Trans. Ind. Electron., vol. 60, no. 11, pp. 4913- 4919, Nov. 2013.

[12] B. Bilgin, A. Emadi, M. Krishnamurthy, “Comprehensive evaluation of the dynamic performance of a 6/10 SRM for traction application in PHEVs,” IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2564-2575, July.2013.

[13] M. Takeno, A. Chiba, N. Hoshi, S. Ogasawara, M. Takemoto, M. A. Rahman, “Test results and torque improvement of the 50-kW switched reluctance motor designed for hybrid electric vehicles,” IEEE Trans. Ind. Appl., vol. 48, no. 4, pp. 1327-1334, Jul/Aug. 2012.

[14] A. Chiba, M. Takeno, N. Hoshi, M. Takemoto, S. Ogasawara, M. A. Rahman, “Consideration of number of series turns in switched-reluctance traction motor competitive to HEV IPMSM,” IEEE Trans. Ind. Appl., vol. 48, no. 6, pp. 2333-2340, Nov/Dec. 2012.

[15] I. Boldea, L. N. Tutelea, L. Parsa, and D. Dorrell, “Automotive electric propulsion systems with reduced or no permanent magnets: an overview,” IEEE Trans. Ind. Electron., vol. 60, no. 9, pp. 5696- 5710, Oct. 2014.