Combined Current Control Strategy for EV-HESM

Nadia A. Elsonbaty[1], Mohamed A. Enany[1], Mahmoud I. Hassanin[2]
[1]Electrical Power & Machines Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt
[2]Electrical Department, Faculty of Engineering, Egyptian Russian University, Bader city, Egypt

Abstract: -*This paper presents a novel control strategy for Hybrid Excitation Synchronous Motor (HESM), In Which both armature and DC field windings are located in the stator* **.**
The resulting control strategy meets the desired characteristics of electric vehicle (EV) and hybrid electric vehicles (HEV) motors. A detailed mathematical model in both steady state and dynamic mode is provided for HESM. The deduced current control strategy based on a combination between field current control (If) and zero direct axis control (ZDAC). Flux regulation is done by keeping field current (If) constant near at its rated value for high acceleration Constant Torque (CT) region. For high speed Constant power region field current is reduced till zero at maximum speed. The conventional flux regulation strategy is done by reversing field current (If) to achieve an oppose flux that regulates the main motor flux. A comparison between the deduced flux regulation strategy and the conventional control strategy is held in steady state mode to show the effectiveness of the proposed strategy on the motor performance characteristics seeking for high acceleration and wide stable constant power speed range without over design. A dynamic Simulation comparison between using ZDAC in combination with the selected If reduced control strategy and without using it is carried out .The simulation dynamic results showed more stability, higher efficiency with using ZDAC in combination with If reduced control pattern.

Index Terms*: hybrid excited synchronous motor, Hybrid Electric Vehicles, Electric Vehicles, Zero Direct Axis Control, flux regulation.*

NOMENCLATURE

V_{ds}, V_{qs}	d- and q-axis stator voltage components
I_d, I_q	d-q-axis armature inductance current components
ψ_d, ψ_q	the d- and q-axis flux linkage components
ψ_{pm}, ψ_f	the permanent magnet and excitation flux linkages
$\emptyset_{pm}$	the permanent magnet flux
ω_r, p	the electrical angular velocity and pair poles numbers
L_d, L_q	the d- and q-axis inductances
M_{sf}	stator & excitation windings mutual inductance
V_f, I_f	The excitation voltage and current.
R_s, R_c	the stator winding and core resistances
E_d, E_q	the d- and q-axis induced EMF components.
R_f, L_f	the excitation winding resistance& inductance
T, N	the motor torque and mechanical speed
N_r, N_b, N_m	the mechanical rated, base & maximum speed
V_s, ψ_s	the stator voltage & flux linkage
ω_s, SR	the electrical synchronous speed & speed ratio
E_a, I_a	the armature (stator) induced voltage & current

I_{fr}	the rated field current
E_{ao}, ψ_{do}	the no load armature EMF & d- axis flux linkage

I. INTRODUCTION

HEV's motor drives are the wide speed constant power capability and the high operational efficiencies as well as having the characteristics of low-speed high-torque hill climbing, high torque density (Nm/Kg), high power density (KW/Kg) and minimum size [1-3].

Motors for vehicle application should, therefore be designed with very thin laminations as far as the efficiency is concerned [4]. The permanent magnet motors have an advantage over all other motors. However, at speeds beyond the base speed, weakening of the permanent magnet field requires an additional stator negative current component. This would lower the efficiency and power factor which in turn has a direct impact on the sizing of the power converter [1].

In order to overcome this drawback, kinds of hybrid excitation synchronous motors (HESM) have been proposed [5-6].

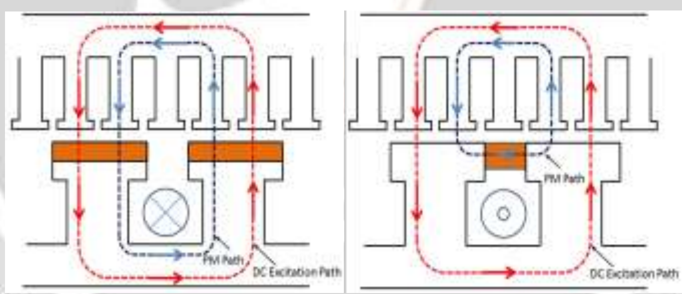
HESM consists of a combination between two excitation sources (field winding sources and Permanent magnets (PMs)) which make it have many advantages as summarized as follow [5-6].

1- Flux-regulation capability in all modes is better.

2-Good alternative to PM alternators with power converter in case of generating mode

3- Easy to achieve high-speed operation with higher energy efficiency in case of motoring mode.

The PMs provide the constant flux and the field current can boost or weaken the overall flux. HESM are classified into two main classes: series HESM (DC coils excitation flux passes through PM) and parallels HESM (DC coils excitation flux paralyze the PM flux)as shown in Fig.1 [7].



(a) Series HESM, (b) Parallel HESM

Fig.1 Main types of HESM

In series structures, the DC field winding flux crosses the PM flux resulting in high reluctance. Thus, high field current is needed for flux weakening causing high copper losses and the risk of PM demagnetization. In parallel structure the PM flux and the DC field flux are superimposed in the air gap and the armature windings only. The machine presented here belongs to the second class.

Several HESM control techniques have been presented [8–9]. In [10] fuzzy control technique was developed for hybrid excitation BLDC motor based on regulating d-axis and excitation current using fuzzy controller. A dynamic vector control model was developed by Shinnaka [11] and then zero d-axis current based copper loss minimization vector control approach was tested for non-salient pole HESM [12]. In [13] a simplified subsection control method was compared with zero excitation current control method. Improving the stability and efficiency of HESM particle swarm optimization technique was combined with fuzzy control technique in [14]. Based on self optimization of excitation current variable step-size search theory was presented in [15]. In [16] different flux weakening control algorithms are presented. A New flux-weakening control method for speed control in constant power high speed

region was deduced in [8] based on invariable q-axis back-EMF with copper loss reduction. An adaptive constant power high speed region Control technique was deduced in [17].
This paper presents an Efficient Control strategy for EV- HESM and is organized as follows.
In Section II, the construction of HESM in terms of the PM and dc field winding location, stator and rotor sectionalized view and a magnetic structure termed the consequent-pole PM (CPPM) machine is provided.
In section III, Equivalent circuit model of HESM is provided with equations for efficiency calculation.
The proposed (If) reduced control methodology is presented over the two operating ranges (CT & CP) and compared with the conventional(If) reversed current in section IV.
In section V dynamic simulation work is carried out to compare the effectiveness of the proposed If reduced strategy with and without ZDAC. Finally, the conclusions are given in Section VI.

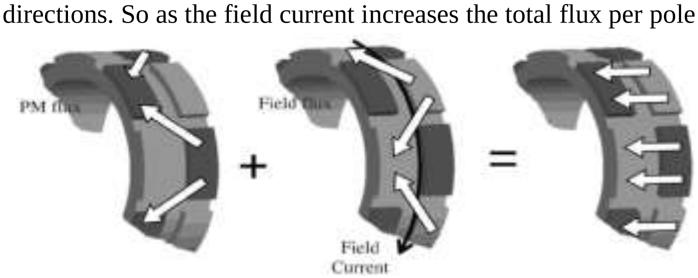
II. CPPM MACHINE TOPOLOGY

There are different structures of hybrid excitation machines that are classified by the rotor construction and the PM position in the machine.
The presented HESM belongs to the Consequent Pole PM (CPPM) construction. The stator comprises laminated core on which the conventional 3-phase armature windings are inserted while the DC field winding is wound on an external yoke [5]. Thus no sliding contacts are needed as shown in Fig.2.

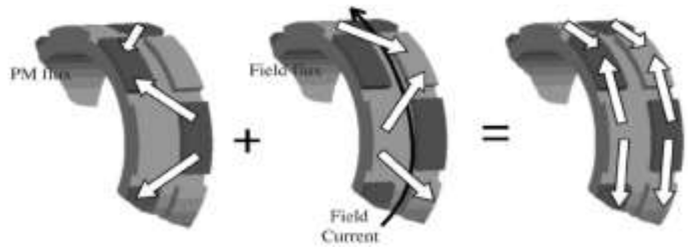
Fig. 2CPPM machine structure [18].

A. Magnetizing effect of the field flux in CPPM Machine

The machine has two fluxes (PM flux and Field winding flux), the relation between them depends on the direction of field winding current or field current (FC). Fig .3 describes the two cases of the magnetizing effect of the field flux on PM flux. Fig. 3 (a) depicts demagnetizing effect of the field flux, machine fluxes cross the air gap in opposite directions. So as the field current increases the total flux per pole decreases. If the FC is reversed, another effect is appeared as shown in Fig. 3 (b) which depicts magnetizing effect of the field flux, machine fluxes cross the air gap in same directions. So as the field current increases the total flux per pole increases.



(a) Demagnetization effect



(b) Magnetization effect

Fig. 3Magnetizing effect of the field flux [18].

B. Advantages and Disadvantages of CPPM machine

Comparing with traditional PM machines, CPPM machine introduces many advantages such as [18];
1- Low FC required for wide range of flux control
2- Absent of demagnetization risk of core during flux control
3- Absent of slip rings and brushes
4- Simple FC control is available
But in other hand there are some drawbacks due to its structure.
1- Lower power density machine due to the presence of field winding in stator
2- Extra losses due to tangential and axial flux distribution.

III. HESM Mathematical Model for EV Application

Fig.4 illustrates the HESM equivalent circuit [19], from which the following mathematical model is deduced.

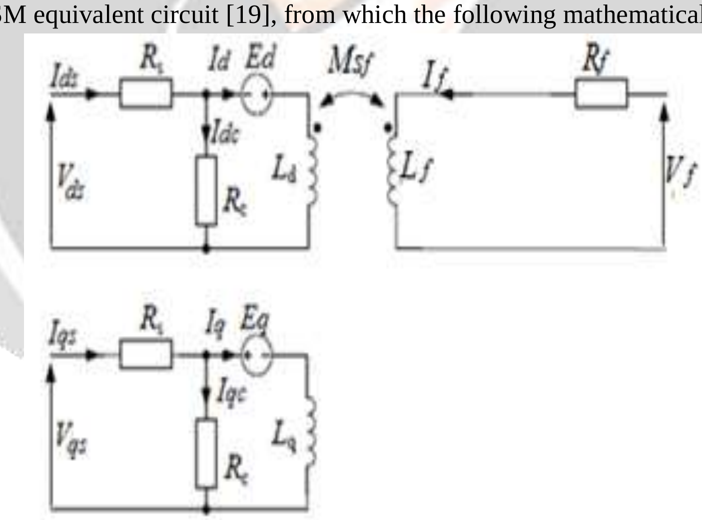


Fig.4 HESM Equivalent Circuit.

The stator voltage dynamic equations can be written in synchronous *d–q* reference frame, as follow [17];

$$V_{ds} = R_s I_d + \frac{d}{dt}\psi_d - \omega_r \psi_q \quad (1)$$

$$V_{qs} = R_s I_q + \frac{d}{dt}\psi_q + \omega_r \psi_d \quad (2)$$

Where the Flux linkage equation can be given as shown;

$$\psi_d = \psi_{pm} + L_d I_d + M_{sf} I_f \quad (3)$$

$$\psi_q = L_q I_q \quad (4)$$

So the stator voltage equations can be rewritten as follow

$$V_{ds} = R_s I_d + L_d \frac{d}{dt} I_d + E_d \quad (5)$$

$$V_{qs} = R_s I_q + L_q \frac{d}{dt} I_q + E_q \quad (6)$$

Where;

$$E_d = -\omega_r L_q I_q \quad (7)$$

$$E_q = \omega_r \left(\psi_{pm} + L_d I_d + M_{sf} I_f\right) \quad (8)$$

So the stator voltage equations can be expressed as follow;

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_f \end{bmatrix} = \begin{bmatrix} R_s + sL_q & \omega_r L_d R & \omega_r M_{sf} R \\ -\omega_r L_q R & R_s + sL_d & 0 \\ 0 & 0 & R_f + sL_f \end{bmatrix} \begin{bmatrix} I_q \\ I_d \\ I_f \end{bmatrix} + \begin{bmatrix} \omega_r \psi_{PM} R \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

Where;

$$R = 1 + \frac{R_s}{R_c} \quad (10)$$

Note that $s = \frac{d}{dt} = 0$ at steady state operation.

Electromagnetic torque equation can be expressed as follow;

$$T = \frac{3}{2} p I_q \left(\psi_{pm} + \psi_f + (L_d - L_q) I_d\right) \quad (11)$$

Where;

$$\psi_f = M_{sf} I_f \quad (12)$$

This is a sum of hybrid torque and a reluctance torque.

IV. Proposed Reduced Field Current Control Strategy

In interior PM machine (IPM), to avoid the reluctance torque effect confuse weather it is strengthen or weakening duo to the PM location (L_d > *or* < L_q), zero *d*-axis current (ZDAC) control strategy is applied as shown by the HESM phasor diagram of Fig 5. Constant torque region and constant power region require different control techniques for each one as proposed in the following sections. The PM poles provide the major part of air-gap flux, while the wound field excitation poles act as a flux regulator to adjust the air-gap flux distribution.

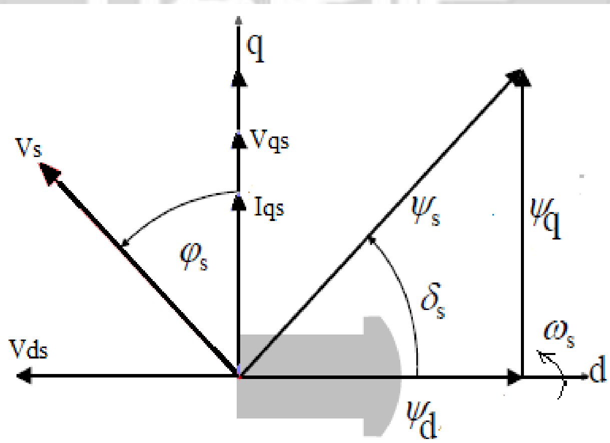


Fig. 5 HESM phasor diagram with ZDAC

IV.1. Constant Flux High Torque region (CT).

In ideal condition but not practically the EV motor may operate directly in the high speed constant power region for both motoring and regenerating regions. Alternatively, a high acceleration as possible is required to fulfill the required wide constant power speed range (CPSR) for EV. If a PMSM with the same CPSR as the original motor was to be used, it would cause a forbidden over design. Speed lower than the rated speed is known as base speed, N_b , it is defined and it's characteristic is detailed in section V.
To produce high starting constant torque up to a base speed where rotor speed, $N < N_b$. ZDAC strategy ($I_d = 0$) is applied. Within this speed range, both of PM and constant excitation field fluxes produce constant flux. They are superimposed in the air gap and armature winding. The field current is nearly at its rated value (95% of rated value) to create 30%of the PM flux for field strengthening. the iron loss equivalent resistance can be neglected [8].

IV.2 Constant power High Speed region (CP)

In this region the difference between the presented field current control (reduced If) strategy and the conventional field current control strategy (reversed If) is carried out as follow :
When higher rotor speed than base speed is needed ($N > N_b$), unlike the CT, the field current must be adjustable. It may be reduced or even reversed to weaken the flux. Figs. 6 - 12 illustrate the field current effect (descending positive down to zero and descending positive down to its negative rated value) on HESM characteristics.
Fig.6 shows that positive field remarkably extends the CP operating speed range speed. With positive &negative If control, the reversed If reaches its rated value at a remarkable lower speed. Extended CP is obtained at lower input power as shown in Fig.7.

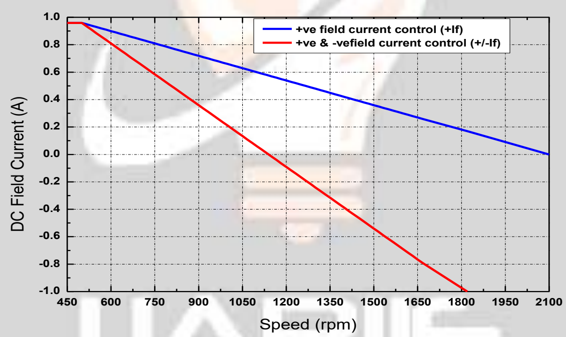


Fig.6, Speed range with reduced & reversed field current at +If and +/-If.

Fig. 8 depicts the stator voltage at + If is nearly constant in correspondence of the two CT and CP regions. Thus improved stability at less $\frac{dv}{dt}$ stress will be obtained. The dq current and voltage components are provided for current or voltage control strategies by Figs. 9 and 10 respectively.
Fig.9 clearly shows that in + If technique, the q-axis current changes proportionally to $1/\omega_r$, in order to maintain constant power in this region. This explains the constant reactive voltage drop E_d (eq.7) and consequently V_{ds}, given in fig.10.
In addition, Fig. 9 declares the remarkably stator current reduction with speed increase + If technique. This explains the resulted higher efficiency shown in fig.12.
Figure.11 depicts the corresponding ψ_{pm}, ψ_f and ψ_{max} at + ve (reduced If) technique as compared with + ve / -ve (reversed If). Fig.12 illustrates both efficiency and Power factor for both systems.

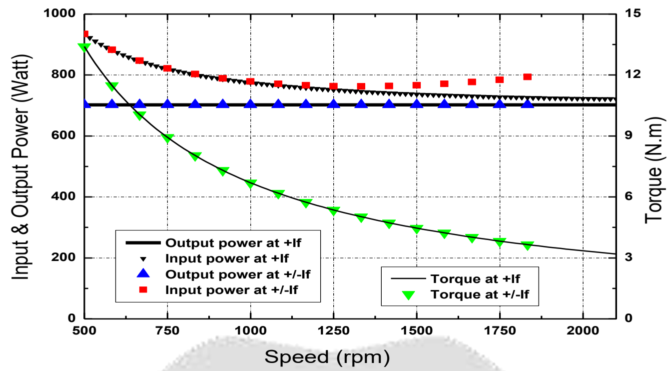


Fig. 7, Output, Input Power and Torque with reduced& reversed field current (If) control.

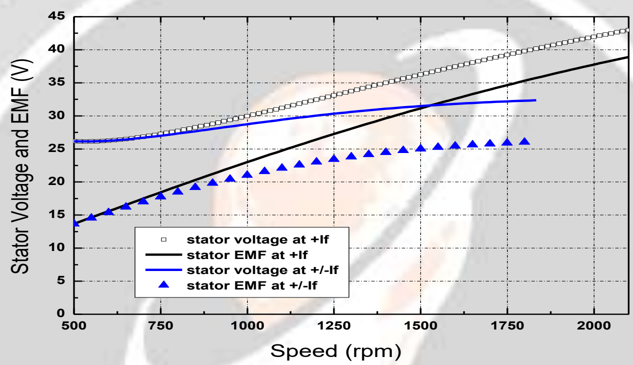


Fig. 8, Stator Voltage and EMF with reduced &reversed field current (If) control.

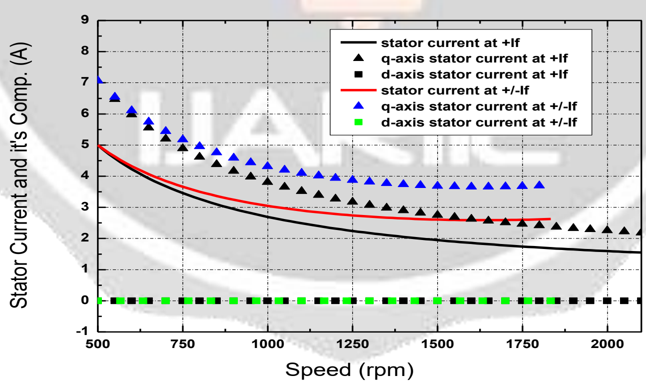


Fig. 9, Stator Current and it's components with reduced & reversed field current (If) control.

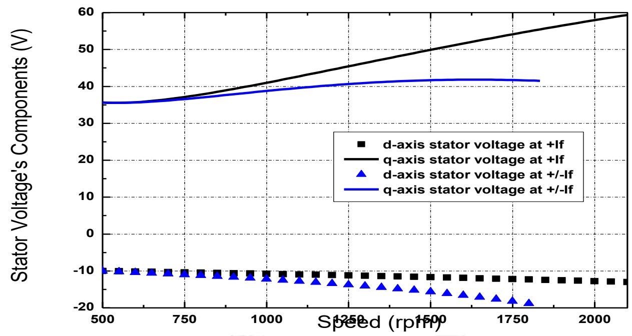


Fig. 10, Stator Voltage components at reduced & reversed field current (If) control

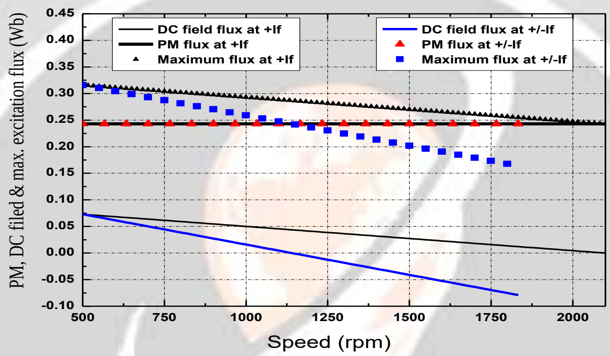


Fig. 11, PM, DC Field and Maximum excitation flux with reduced & reversed field current (If) control.

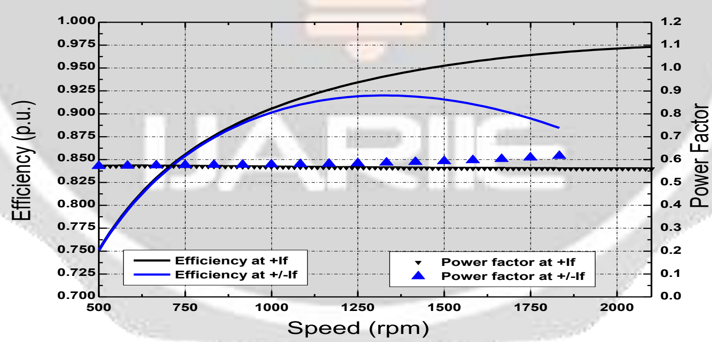


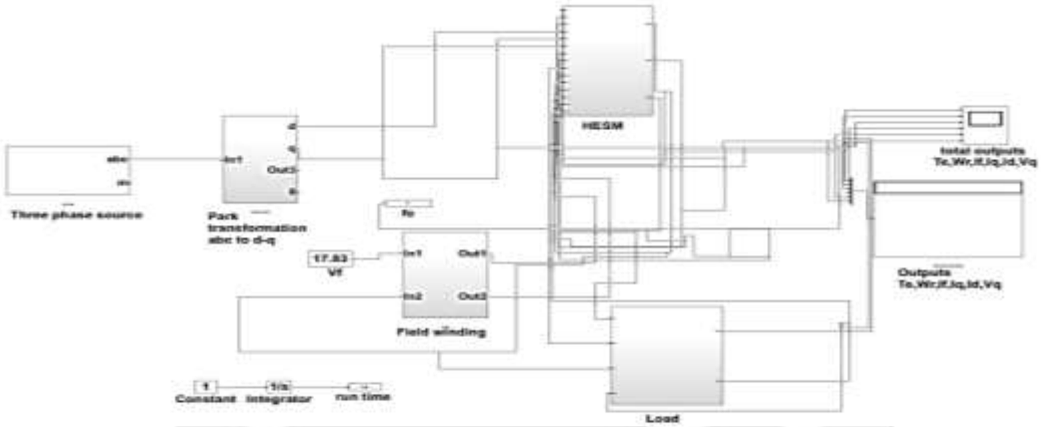
Fig.12, Efficiency and Power Factor with reduced & reversed field current (If) control.

From this comparison it's clear that that the proposed control strategy of reducing If in combination with ZDAC has the advantage of high starting torque , lower losses and higher efficiency than the conventional control strategy of reversing field current (If) .

V. Simulation Works

To verify the efficiency of the proposed combined strategy, Using Matlab Simulink with the dynamic circuit equations to build the motor model as shown in Fig.13.

This model also confirm stability of the steady state model and the effectiveness of the combination of reduced If current strategy
with ZDAC.



.

Fig. 13 Matlab/ Simulink model of HESM

With the use of dynamic simulation model stability can be approved at different speeds. This model will greatly simplify the proposed control strategy. The given mathematical model equations (sec II) with constant FC (corresponding to field flux = 30% of the PM flux) are applied for CT region. For field weakening flux, the field current is decreased steeply up to zero value. A comparison between using the combined reduced field current (If) with and without ZDAC was held and the results was as the following;

Fig. 14 shows the resultant output speed , power and torque from the Simulink model at reduced If with and without ZDAC ,as below

(A) at frequency of *5 Hz* (CT, *very low frequency),*

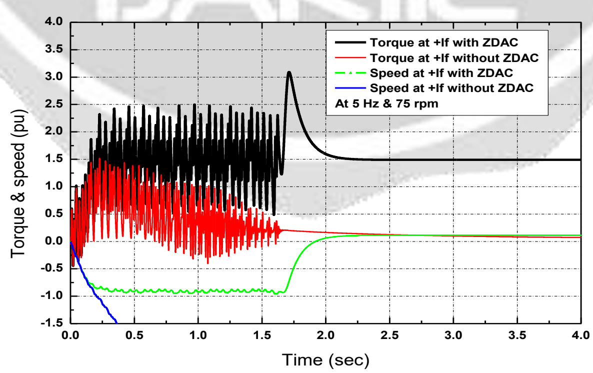
(B) at frequency of *22.2 Hz* (CT, *low fequency*).

(C) at frequency of *33.3 Hz* (CT, *base fequency*).

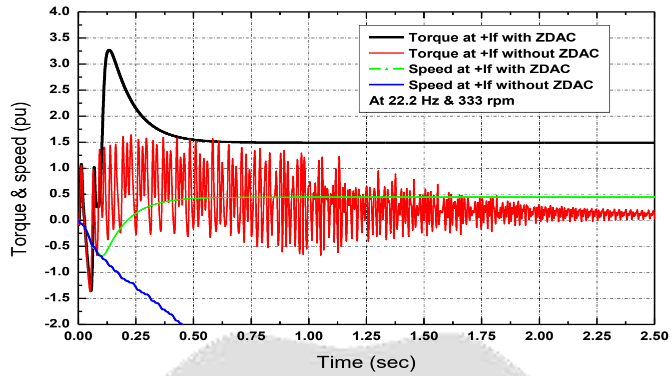
(D) at frequency of *50 Hz* (CP, *rated fequency*),

(E) at frequency of *75 Hz* (CP, *high fequency*).

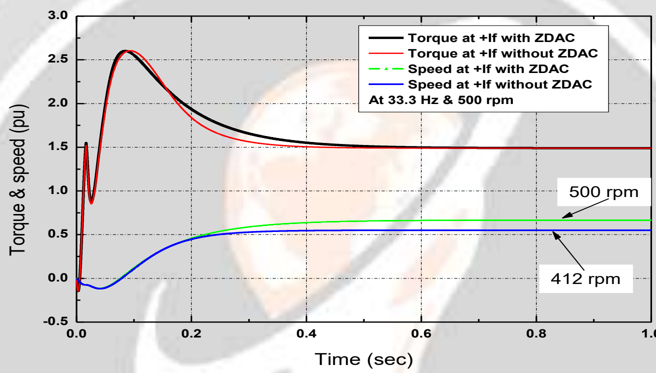
(F) at frequency of *100 Hz* (CP, *very high fequency*).



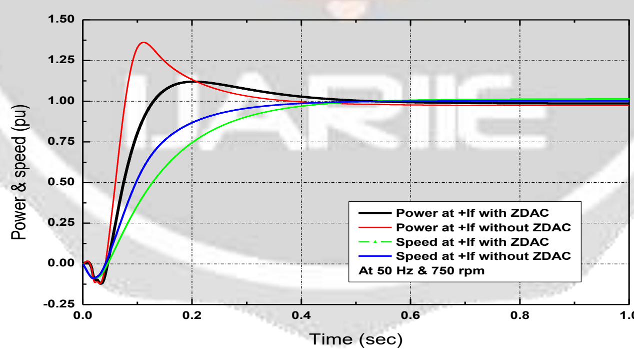
(a) output speed and torque at +If with and without ZDAC at frequency of 5 Hz



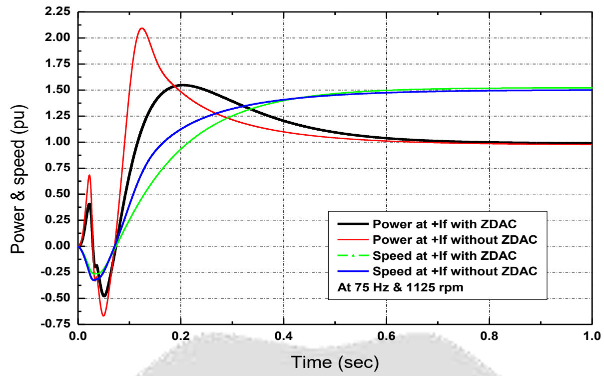
(b) output speed and torque at +If with and without ZDAC at frequency of 22.2 Hz



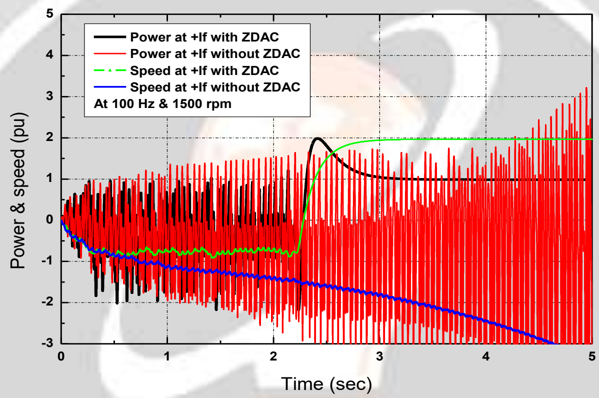
(c) output speed and torque at +If with and without ZDAC at frequency of 33.3 Hz



(d) output speed and power at +If with and without ZDAC at frequency of 50 Hz



(e) output speed and power at +If with and without ZDAC at frequency of 75 Hz



(f) output speed and power at +If with and without ZDAC at frequency of 100 Hz

Fig. 14 output speed , power and torque at +If with and without ZDAC at different frequency.

From figs. 14 (a) and (b); it is clear that for low frequencies (CT region), HESM at + If without ZDAC is unstable while + If with ZDAC stabilizes the motor at maximum torque. At base frequency HESM gains its stabilty at the same time but with a higer (base) speed at ZDAC as shown in fig. 14(c). An over shot stabilty occures at rated and high frquency at + If without ZDAC as shown in fig. 14(d). At three times base frequency, HESM looses its stability at + If without ZDAC as shown in fig. 14(f).

VI. Conclusion

1- The paper introduce an optimum control strategy that fulfills the favorite required EV-motor Characteristics such as high acceleration, high efficiency, wide extended CPSR, low maintenance (as it has no slides) and stable operation.
2- Positive field current control over the whole CPSR is much more efficient than that with reversed current.
3- It declares that high acceleration with high efficiency requires the CT region base speed < rated speed at maximum torque operation
4- CT operation at rated torque –rated speed suits only light loads, with less CPSR.
5- Current and voltage control techniques are provided to suit any required system.
6- Simulink model has been validated through comparison t the effectiveness of combined current control strategy in EV HESM.

VII. APPENDIX

The parameters of motor under study are shown below [8];

p	*4*
N_b	*500 rpm*
N_r	*750 rpm*
T_r	*9 N.m*
T_b	*13 N.m*
I_{sr}	*5 A*
I_{fr}	*1 A*
P_r	*700 Watt*
R_s	*2.7 ohm*
R_f	*33 ohm*
L_d	*38 mH*
L_q	*27 mH*
L_f	*0.57 H*
M_{sf}	*76 mH*
$\emptyset_{pm}$	*0.243 Wb*

VIII. REFERENCES

[1] T. A. Huynh, and M. Hsieh," Performance Analysis of Permanent Magnet Motors for Electric Vehicles (EV) Traction Considering Driving Cycles", Energies Vol. 11 , Issue: 5 , no. 1385, pp. 1-24 2018, 11, 1385; May 2018

[2] M. Villani, " High Performance Electrical Motors for Automotive Applications – Status and Future of Motors with Low Cost Permanent Magnets", in WMM-18–8th International Conference Magnetism and Metallurgy, June 12-14, 2018, Dresden, Germany.

[3] P. D. Barba , M. Bonislawski , R. Palka , P. Paplicki , and M. Wardach, "Design of Hybrid Excited Synchronous Machine for Electrical Vehicles", IEEE Transactions on Magnetics, Vol. 51 , Issue: 8 ,pp. 1-8, Aug. 2015

[4] I.Urquhart, D.Tanaka, R. Owen, Z.Q.Zhu, J.B Wang, and, D.A Stone," Mechanically actuated variable flux IPMSM for EV and HEV applications", EVS27, International Battery, Hybrid and Fuel Cell Vehicle Symposium 1, pp. 684-695, November 17-20, 2013 ,Barcelona, Spain.

[5] S. Asfirane, S. Hlioui , Y. Amara , and M. Gabsi ," Study of a Hybrid Excitation Synchronous Machine: Modeling and Experimental Validation ", Mathematical and Computational Applications, Vol. 24 , Issue: 2 , no. 34, pp. 1-27, March 2019

[6] S. Hlioui , Y. Amara ,E. Hoang, M. Lecrivain and M. Gabsi ," Overview of Hybrid Excitation Synchronous Machines Technology ", International Conference on Electrical Engineering and Software Applications (ICEESA),pp.1-10, March 2013, Hammamet, Tunisia

[7] E. Yildiriz, and G. Önbilgin, " Design studies of Axial Flux Hybrid Excitation Synchronous Machine with magnetic bridge", 8th International Conference on Electrical and Electronics Engineering (ELECO), pp. 234-237, November 28-30, 2013, Bursa, Turkey.

[8] H. Mingming, G. Xingjun, J. Ping, H. Quanzhen, L. Yuping, and L. Na, "Flux-weakening control methods for hybrid excitation synchronous motor", ARCHIVES OF ELECTRICAL ENGINEERING Vol. 64, No.3, pp. 427-439, 2015

[9] G. Borocci,, F. G. Capponi, G. D. Donato, and F. Caricchi, “Closed-loop flux-weakening control of hybrid-excitation synchronous machine drives,” IEEE Trans. Ind. Appl., Vol. 53, No. 2, 1116–1126, Dec. 2017

[10] J.J. Chen, " Automatic flux-weakening control of permanent magnet synchronous motors using a reduced-order controller," IEEE Trans. Ind. Electr., Vol. 15, No. 5, pp. 881–890, Sep. 2000

[11]S. Shinnaka, " New dynamic mathematical model and new dynamic vector simulators of hybrid field synchronous motors", IEEE International Conference on Electric Machines and Drives, pp. 882–889, 2005, San Antonio, TX, USA

[12] S. Shinnaka, " New optimal current control methods for energy-efficient and wide speed-range operation of hybrid-field synchronous motor,” IEEE transactions on industrial electronics, Vol. 54, No. 5, pp. 2443–2450, July 2007.

[13] C.F. Yang, H. Y. Lin, J. Guo, and Z. Q. Zhu,"Design and analysis of a novel hybrid excitation synchronous machine with asymmetrically stagger permanent magnet,” IEEE Trans. Magn., Vol. 44, No. 11, 4353–4356, Dec. 2008.

[14] M. M. Huang, H. Y. Lin, Y. K. Huang, P. Jin, and Y. J. Guo, “Fuzzy control flux weakening of hybrid excitation synchronous motor based on particle swarm optimization algorithm,” IEEE Trans. Magn., Vol. 48, No. 11, pp.2989–2992, Oct. 2012.

[15] W.J. Wang, and Z.R. Zhang, "Maximum torque control of hybrid excitation synchronous machine drives based on field current self-optimizing method. IECON Proceedings: pp. 2977-2982 (2013).

[16] F.G. Capponi, G. Borocci, D. Donato, and F. Caricchi," Flux Regulation Strategies for Hybrid Excitation Synchronous Machines", Energy Conversion Congress and Exposition (ECCE), 2014 IEEE: 4858- 4865 (2014).

[17] Y. Zhang, Q. Huang, M. Huang, D. Decker, and Y. Qing, "Design and Experimental Verification of Adaptive Speed Region Control for Hybrid Excitation Claw-Pole Synchronous Machine", Progress In Electromagnetics Research C, Vol. 88, pp.195–205, 2018

[18] J. A. Tapia, F. Leonardi, and T.A. Lipo, " Consequent-Pole Permanent-Magnet Machine With Extended Field-Weakening Capability", IEEE transactions on industrial applications, Vol. 39, No. 6, pp. 1704–1709, Nov./Dec. 2003.

[19] Y. Amara, L. Vido , M. Gabsi, E. Hoang, A. Ahmed, and M. Lecrivain " Hybrid Excitation Synchronous Machines:Energy-Efficient Solution for Vehicles Propulsion", IEEE transactions on vehicular technology , Vol. 58, No. 5, pp. 2137–2149, June 2009