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Performance analysis of Electric Vehicles in terms of Constant Power Speed Range (CPSR)

Sudipa Kotal, Supratim Naskar, Roshan Kumar Jha, Subhasis Debnath, Anuradha Mukherjee, Mousumi Jana Bala

***Abstract*— The paper analyses and draws the comparison in terms of constant power speed range (CPSR) of line start permanent magnet synchronous motor (LSPMSM) useful for electric mobility applications. Application of new technology to reduce energy consumption and emissions has become prime factor for the development of automobile technology. CPSR is the most important parameters of permanent magnet motors being used in EV applications. Use of less amount of rare earth permanent magnet, an excellent CPSR makes the LSPMSM favorable in EV application. Still CPSR obtained by analytical methods provides a lower precession as saturation is neglected CPSR can be obtained by using FEA (Finite element analysis) which demands significant computation time. In electric vehicle application, a prime factor for selecting motor is the field flux weakening capability defined by constant power speed zone. Appropriate measures have been taken to determine the desired value of CPSR of the PMSM.**

***Index Terms*-- demagnetization, flux weakening, current angl, flux linkages, permanent magnet material, FEA analysis**

I. Introduction

THE evolution of Electric Vehicles (EV) in the urban perspective is only matter of time, as the adoption of zero emission vehicles, whether they are powered by chemical accumulators or by fuel cells, has become necessary, for the benefit of the society. Indeed, this adoption will be gradual, also for the related need of infrastructures, but it has been accepted already that EVs will be the solution for urban mobility in the near future [1].

Electrical machines designing is a multi-objective complex problem, whose main perspectives are to maximize the output power and torque by minimizing different losses, torque ripple etc. with the reduction of the mass, and expenses.

Sudipa Kotal: Final year in Undergraduate degree in Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

Supratim Naskar: Final year in Undergraduate degree in Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

Roshan Kumar Jha: Final year in Undergraduate degree in Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

Subhasis Debnath: Final year in Undergraduate degree in Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

Anuradha Mukherjee: Final year in Undergraduate degree in Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

Mousumi Jana Bala: Department of Electrical Engineering, Meghnad Saha Institute of Technology, Kolkata

LSPMSMs are making their application in EVs as well as in global markets widely due to their high power to mass density ratio, improved power factor (near to unity) and higher efficiency. Remanence (B_r), Coercivity (H_c), maximum energy product (BH_{max}) and maximum operating temperature are the prime parameters to select the permanent magnet for any PMSM. Advancement in generation of wind power, use of electric vehicles and electronic components in last few years increased the demand of permanent magnet specially Neodymium Iron Boron or NdFeB. Now once, the permanent magnet is chosen, and the electric motor is being designed, another vital factor comes into account for performance analysis of PMSM is the CPSR (constant power speed range) in case of EV applications.

In this paper, appropriate measures have been taken in order to select the permanent magnet material for PMSM based on its various parameters and demagnetization characteristics. Temperature, maximum energy product, coercivity and remanence are considered as prime selection parameters among which the priority is temperature followed by remanence and then followed by other parameters. Now, when the appropriate magnetic material has been chosen, a bar type model of a 10-kW interior LSPMSM rotor has been designed and analyzed for minimum constant power speed range($CPSR_{min}$) and maximum constant power speed range ($CPSR_{max}$) respectively with two selected PM material. Each model has been analyzed with Finite Element Analysis (FEA) using Maxwell software for determining different machine parameters and subsequently solved analytically in MATLAB environment with the derived parameters to determine the CPSR [2].

The $CPSR_{max}$ is calculated for the min torque and the $CPSR_{min}$ for rated power. The base value of speed has been calculated at T_{max} and peak value of power. The type of permanent magnet material has an important role for motor performance parameters and it controls the range of Constant Power Speed Range. Depending upon the necessity, appropriate permanent magnets have been considered and the ranges of CPSR have been studied further.

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II. MATHEMATICAL DESIGN

PMSM motor has been designed in d-q reference frame revolving at a speed ω by following steady state equations [3], [4]

$$\begin{cases} i_d = \frac{2}{3}(i_a - 0.5 i_b - 0.5 i_c) \\ i_q = \frac{1}{\sqrt{3}}(i_b - i_c) \end{cases} \quad (1)$$

$$\begin{cases} V_d = -\omega \varphi_q \\ V_q = \omega \varphi_d \end{cases} \quad (2)$$

where, i_d, i_q , V_d, V_q and φ_d, φ_q are the direct axis and quadrature axis current voltages and flux linkages respectively.

Permanent magnet flux linkage φ_{pm} and d and q-axis inductances L_d, L_q are being used to design the direct axis and quadrature axis flux linkages as

$$\begin{cases} \varphi_d = \varphi_{pm} + L_d i_d \\ \varphi_q = L_q i_q \end{cases} \quad (3)$$

here, φ_{pm} is nothing but the flux of the permanent magnet and can be represented as:

$$\varphi_{pm} = L_d I_s \quad (4)$$

In steady state operation, the peak armature current I_{sm} and peak armature voltage V_{sm} can be represented as

$$I_{sm} = \sqrt{(I_d^2 + I_q^2)} \quad (5)$$
$$V_{sm} = \omega \sqrt{(\varphi_d^2 + \varphi_q^2)}$$

That leads to obtain the electromagnetic torque and speed equations as

$$\omega = \frac{v}{p\sqrt{\{(\varphi_m + L_d I_d)^2 + (L_q I_q)^2\}}} \quad (6)$$

$$T = \frac{3}{2}p(\varphi_m I_q + \varphi_d I_d)$$
$$= \frac{3}{2}p(\varphi_m I_q - \varphi_q I_d)$$
$$= \frac{3}{2}p(\varphi_m I_q + (L_d - L_q) I_d I_q) \quad (7)$$

where, p represents the number of pole pairs. The torque developed by the permanent magnet is

$$T_{pm} = \frac{3}{2} p \varphi_m i_q \quad (8)$$

And, reluctance torque is,

$$T_{pm} = \frac{3}{2} p (L_d - L_q) i_d i_q \quad (9)$$

The base speed, ω_{base}, minimum speed, ω_{min} and rated speed, ω_{max} required for calculation of CPSR are defined as follows

$$\omega_{base} = \frac{P_{peak}}{T_{max}} \quad (10)$$

$$\omega_{min} = \frac{P_{rated}}{T_{max}} \quad (11)$$

$$\omega_{max} = \frac{V_{sm}}{P\sqrt{(\varphi_{d2}^2 + \phi_{q^2}^2)}} \quad (12)$$

CPSR calculation is dependent on power, torque and the current angle. The angle by which the current phasor leads q axis is defined by the current angle and is denoted by β (fig.1).

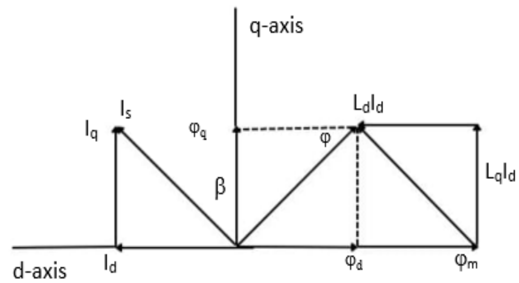

Fig. 1. Phasor diagram

The power and the torque with respect to speed for Electric Vehicle motors have been shown in fig 2.

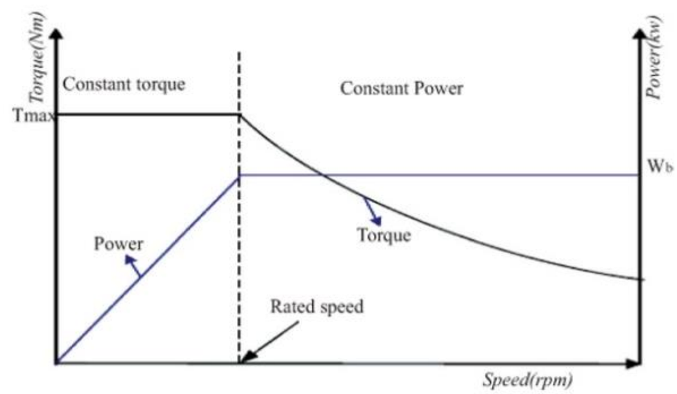

Fig. 2. Torque-Speed and Power-Speed characteristics

In field flux weakening zone, the maximum permissible value of speed is obtained at point W_b by increasing current angle β, degrading the flux of the PM with armature current being kept constant at rated value.

In the flux weakening zone, as I_s follows the locus of the rated current, at the rated voltage, maximum torque T_{max} starts decreasing from its peak value and becomes minimum at point W_b.

III. THEORETICAL BACKGROUND

For PMSM, CPSR has been gained more interest since many years. [5] [6]. Machine parameters are prime responsible factors to mark CPSR finite or infinite. A wide range of CPSR

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is necessary for applications like wind mill and electric vehicle. Constant power speed range is generally used to describe the ratio between the desired maximum speed to the no load speed or rated speed and the range is generally application dependent. The CPSR ratio changes from (2:1) [7] up to (10:1). The PMSMs with large winding inductance possess infinite CPSR whereas the smaller ones possess finite CPSR. The analysis of the surface PMSM in the CPSR has been done in several literatures [8], [9]. Analysis of the PMSM concludes that the lower magnitude of characteristic current ($I_c = -\psi_m L_s$) with respect to the full load current assured theoretically infinite magnitudes of CPSR. This ratio is dependent on the various machine parameters like stator bore diameter, stator outer diameter, stator slots dimensions as well as permanent magnet dimensions etc. Analytical models developed in [10] are capable of obtaining the complete machine parameters in an accurate and fast way. Terminal voltage, inductances, torque, stator core losses and PM losses are the parameters which are involved. These models have to be validated through FEA analysis. This model is used to check the impact of machine parameters on the characteristic current and voltage. For sake of comparison, all the rated parameters like speed, torque and power in both the cases are maintained equal.

IV. Work flow

In the last work [11] a 10 Kw LSPMSM for which the specifications are given in Table I, had been designed on which Finite Element Analysis was done in the MAXWELL environment for its performance. Corresponding to the previous work, systematic sorting of elements in order to find the appropriate permanent magnet material to be used in permanent magnet synchronous motor for electric vehicle operation has been done. In continuation to the previous work, further proceedings with the calculation of CPSR for desired material in order to analyze the performance of the material is to be done.

In the last paper database had been created to find the appropriate material for permanent magnet of the motor considering the values of Temperature, Remanence, Coercivity, Intrinsic Coercivity and Maximum Energy Product. After sorting of the parameters on the basis of the requirement of the user two grades, N50 and N52 were found to be the suitable grades of the material for the desired power speed range. The next job is to find whether the following grades provide the optimum Constant Power Speed Range to improve the performance of electric vehicles. A MATLAB program has been created for the further analysis from which the necessary values required to calculate the CPSR can be obtained. The program gives the direct-axis and quadrature-axis inductance L_d, and L_q respectively and current angle (β) which are necessary to get power and torque for the magnetic material to find the peak and base speed of the machine.

After finding out the necessary values from the MATLAB program the values obtained for different parameters are taken and are put into an excel sheet where necessary calculations have been done from where the maximum and minimum value of CPSR can be found out and thus obtaining the range of CPSR and accordingly the performance of the Electric vehicles can be improved in order to obtain the required torque and speed zone for a vehicle so that the vehicle can cover more distance after getting one time fully charged.

V. Results

To obtain ω_{base} and ω_{max} by equation (10) and (12) respectively, β the current angle has been acquired analytically for maximum torque and maximum power. Current angle at maximum torque, β_{Tmax} and at maximum power, β_{Pmax} with respective speeds have been shown in table II. Max and min Constant Power Speed Range have been calculated for different grades of permanent magnet which are N50 and N52 and shown in table III. Maximum value of power can be obtained at ω_{base} which is the rated value of speed. The peak value of speed $\omega_{max,}$ is obtained at minimum value of torque available at maximum magnitude of β which is 90°. Beyond ω_{max}, the torque would be minimum and the power would be declined to zero if it is left uncontrolled. Max and min Constant Power Speed Range have been obtained by calculations and tabulated for different grade of PM with bar type rotor configuration as shown in table II. Table I shows the specifications of the tested LSPMSM for which CPSR is to be calculated.

From the maximum and minimum CPSR values the CPSR has been found for the required configuration and the values have been provided in the table III. A comparatively higher value of 688.35 rad/sec for ω_{max} has been attained for N50 grade bar type PM with parallel magnetization and 703.57 rad/sec has been obtained for N52 grade. This leads to a CPSR of 2.267 for N50 grade and 2.36 for N52 grade of permanent magnet material.

Fig 4 shows the Power-Beta, Speed- Torque and Speed-Power curves respectively with for parallel magnetization of permanent magnet.

T-ω and P-ω curves regarding parallel magnetization have been displayed in fig 5(b) and fig 5(c) respectively for parallel magnetization of N52 grade whereas fig 5(a) shows the Power-Beta characteristics.

TABLE I
Specifications of tested LSPMSM

Sl. No	Parameters	Value	Unit
1	Power	10/13	kW / HP
2	Rated Voltage	110	V
3	No. of Poles	4	-
4	Frequency	50	Hz
5	Rated Speed	1500	rpm
6	Rated torque	63.69	N-m
7	Power Factor	0.85	-
8	Efficiency	0.95	-
9	Stator Connection	Star	-
10	Frame size	90S	-
11	Operating temperature	75	°C

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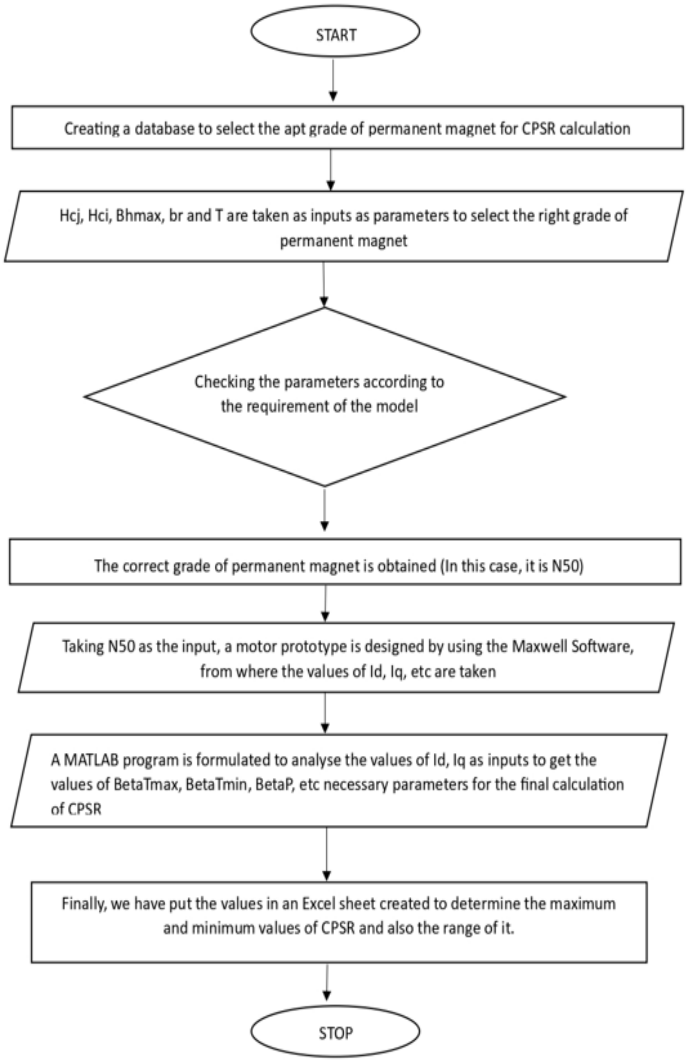

Fig.3. Flow chart for CPSR calculation

TABLE II

Flux linkages and inductances

Parameters \ Grade	N52	N50
i_d,A	90.3	90.8
i_q,A	78.2	79.47
I_{drms}, A	63.85	64.21
I_{qrms}, A	55.3	56.19
Φ_d, wb (Maxwell)	0.427	0.425
Φ_q, wb (Maxwell)	0.4383	0.4373
Φ_d, wb (rms)	0.302	0.301
Φ_q, wb (rms)	0.31	0.309
L_d, mH	4.73	4.69
L_q, mH	7.93	7.78
I_s, A	84.47	85.32
Φ_m, wb	0.4	0.4

TABLE III

Calcuated Maximum Torque, Maximum Power and CPSR

Parameters \ Grade	N52	N50
β_{Tmax}, (degree)	21.17	20.67
β_{Pmax}, (degree)	89.5	88
β_{Tmin}, (degree)	90	90
ω_{min}, rad/sec	124.27	124.9
ω_{base}, rad/sec	244.95	248.38
ω_{max}, rad/sec	703.57	688.35
$(CPSR)_{min}$	0.51	0.503
$(CPSR)_{max}$	2.87	2.77
T_{max}, N-m	80.46	80.06
P_{max} , kW	19.71	19.88
Range_ CPSR	2.36	2.267

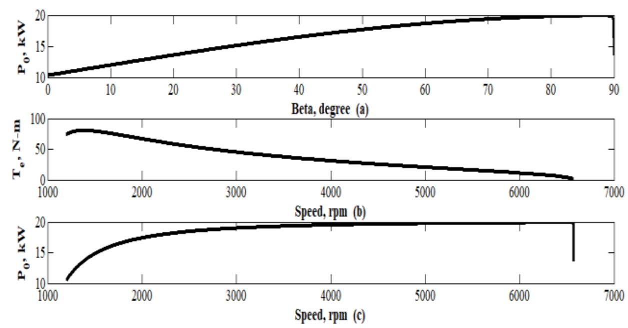

Fig. 4 (a) Power-beta (b) Torque- speed and (c) Output power-speed characteristics for N50 grade parallelly magnetized magnetic material

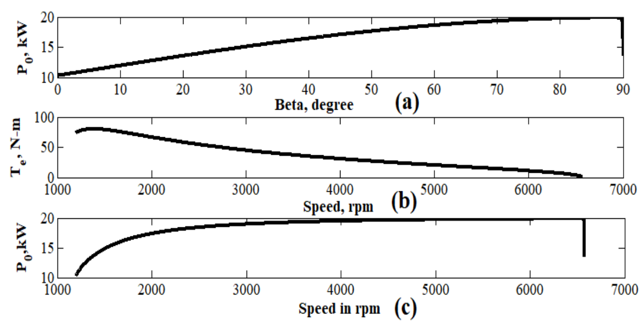

Fig: 5 (a). Power-beta (b) Torque-speed and (c) Output power-speed characteristics for parallelly magnetized of N52 grade magnetic material

VI. Conclusions

We have selected N50 and N52 as suitable grades for optimum performance of PMSM in electric vehicles. Accordingly, a Bar-type motor model has been configured. For calculating maximum and minimum CPSR, maximum and minimum torque and power, have been considered. The bar type model having parallel magnetization has appreciable range of CPSR. Also, it has been observed that N52 grade has a higher range of CPSR than N50 grade. CPSR being a prime

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significant parameter for PMSM involved in Electric Vehicles, there are huge scopes of advance research work for obtaining a wide zone of Constant Power Speed Range for different configurations of rotor with Halbach array magnet arrangement.

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VIII. BIOGRAPHIES

Sudipa Kotal was born in Bankura, (West Bengal) in India, on December, 2000. She is pursuing her final year in Undergraduate degree in Electrical Engineering (2019-2023) from Meghnad Saha Institute of Technology, Kolkata. She completed her higher secondary (XII) from Kenduadihi Girls High School, Bankura (2019) and secondary(X) from Mission Girls High School, Bankura (2017).

Supratim Naskar was born in Kolkata (West Bengal) in India on January 23, 1999. He is pursuing his final year in Undergraduate degree in Electrical Engineering (2019-2023) from Meghnad Saha Institute of Technology, Kolkata. He completed his higher secondary (XII) from Jodhpur Park Boys School, Kolkata (2017) and Secondary (X) from Ramakrishna Mission Vidyapith Purulia (2015).

Roshan Kumar Jha was born in Kolkata, (West Bengal) in India, on July 11, 2001. He is pursuing his final year in Undergraduate degree in Electrical Engineering (2019-2023) from Meghnad Saha Institute of Technology, Kolkata. He completed his higher secondary (XII) from Mansur Habibullah Memorial School, Kolkata (2019) and secondary(X) from Lions Calcutta (Greater) Vidya Mandir, Kolkata (2017)

Subhasis Debnath was born in Kolkata, (West Bengal) in India, on July 30, 2001. He is pursuing his final year in Undergraduate degree in Electrical Engineering (2019-2023) from Meghnad Saha Institute of Technology, Kolkata. He completed his higher secondary (XII) (2019) and secondary(X) (2017) from Calcutta Public School, Kolkata.

Anuradha Mukherjee was born in Kolkata, (West Bengal) in India, on September 5, 2000. She is pursuing her final year in Undergraduate degree in Electrical Engineering (2019-2023) from Meghnad Saha Institute of Technology, Kolkata. She completed her higher secondary (XII) from Mansur Habibullah Memorial School, Kolkata (2019) and secondary(X) from Maharishi Vidya Mandir, Kolkata (2017)

Mousumi Jana Bala was born in West Bengal in India, on January 19, 1976. She completed her Master degree in Electrical Engineering (Specialization Electrical Machines) from Jadavpur University, Kolkata. She graduated from the Bengal Engineering College, Shibpur (Now IIEST), Howrah and studied at the Brahmananda Keshab Chandra College, Barahanagar, Kolkata.

She is an Assistant Professor in the Department of Electrical Engineering in Meghnad Saha Institute of Technology since 2018. She has 20 years of teaching experience in this field. Her field of interest is design of Electrical Machines, modeling of machines and fault analysis.

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