Polar transformed subdomain modeling for primary-segmented permanent magnet linear synchronous machine applied in tracked inspection robots

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Abstract

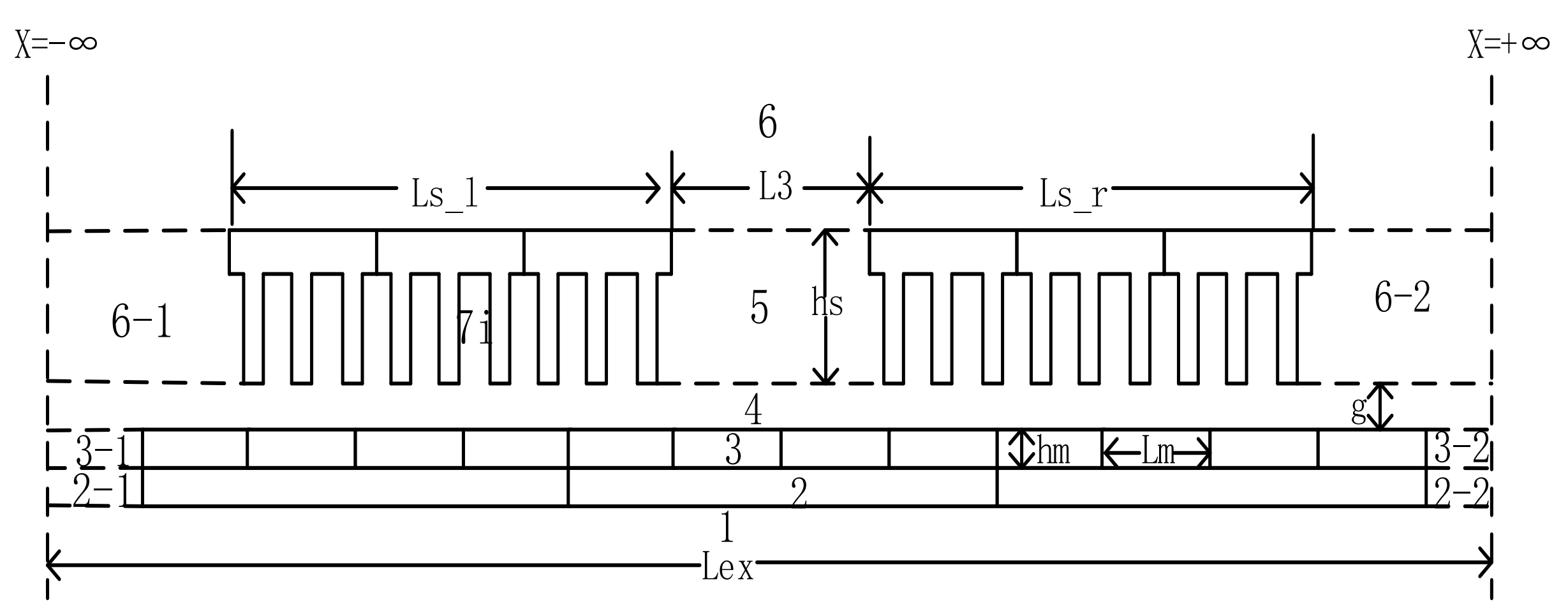
The paper presents an developed analytical subdomain model for design and analysis the primary-segmented permanent magnet linear synchronous machine (PS-PMLSM) accounting for both the primary and secondary end effect. Firstly, the PS-PMLSM is deformed into a ring-segment PMLSM (RS-PMLSM), the analytical model is calculated in Polar coordinates instead of Cartesian coordinates. Then, the subdomain method is adopted to analysis the RS-PMLSM model by solving the Laplace's equation and the Poisson equation in each region, and the slot effect is considered by conformal transformation method. The flux density and back-electromotive force (EMF) are calculated based on the developed analytical model. Finally, the analytical results are verified by the finite-element method (FEM).

Conclusion

- Based on developed analytical subdomain model, the slotting and both the primary and secondary end effects can be considered.
- The analytical solutions were verified by the finite-element analysis, the results were in agreement with the FEA which demonstrates the accuracy of the developed model.
- The analytical model presented in this paper is convenient for initial design processes.

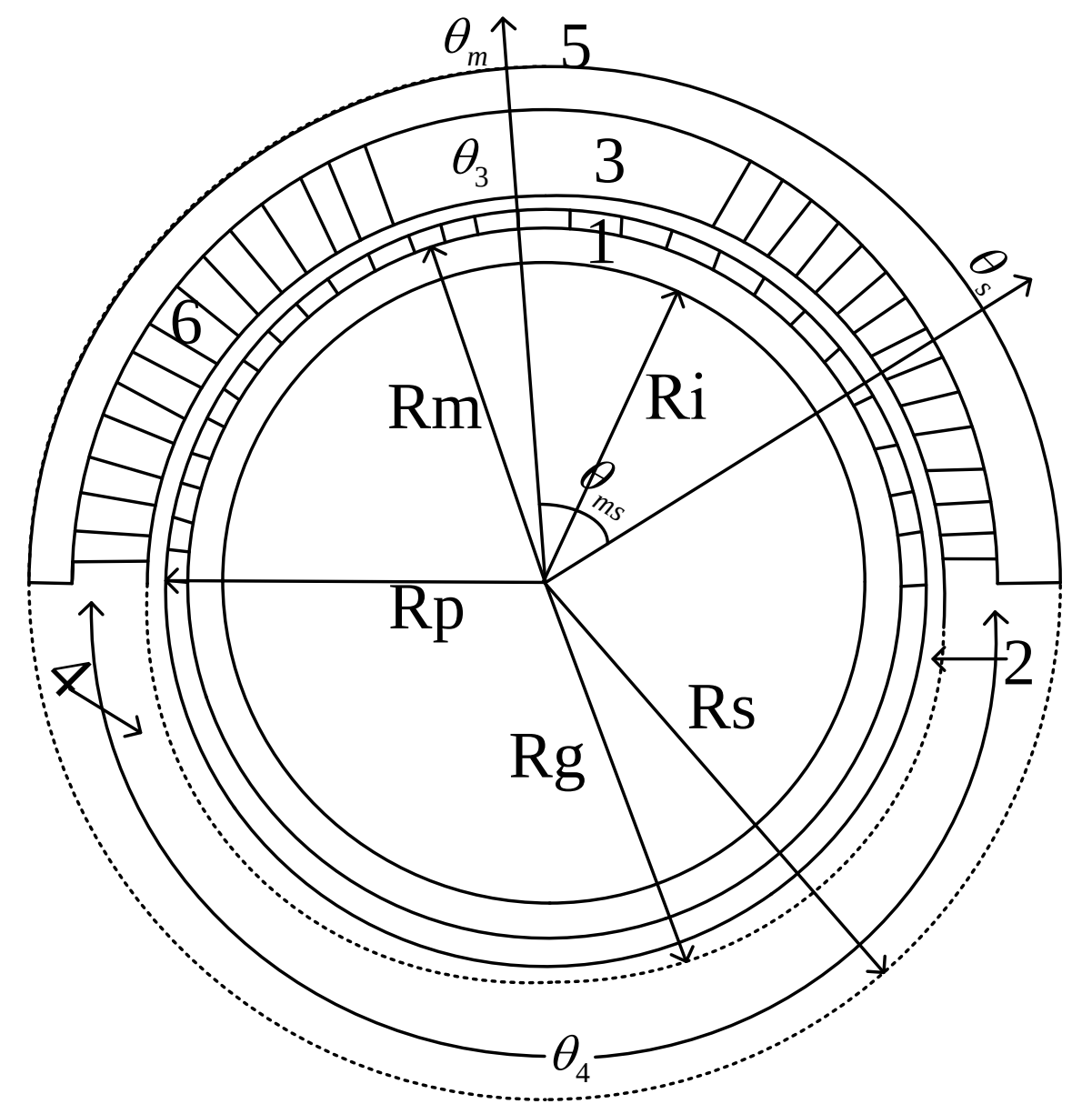
Analysis model

PS-PMLSM in Cartesian coordinates



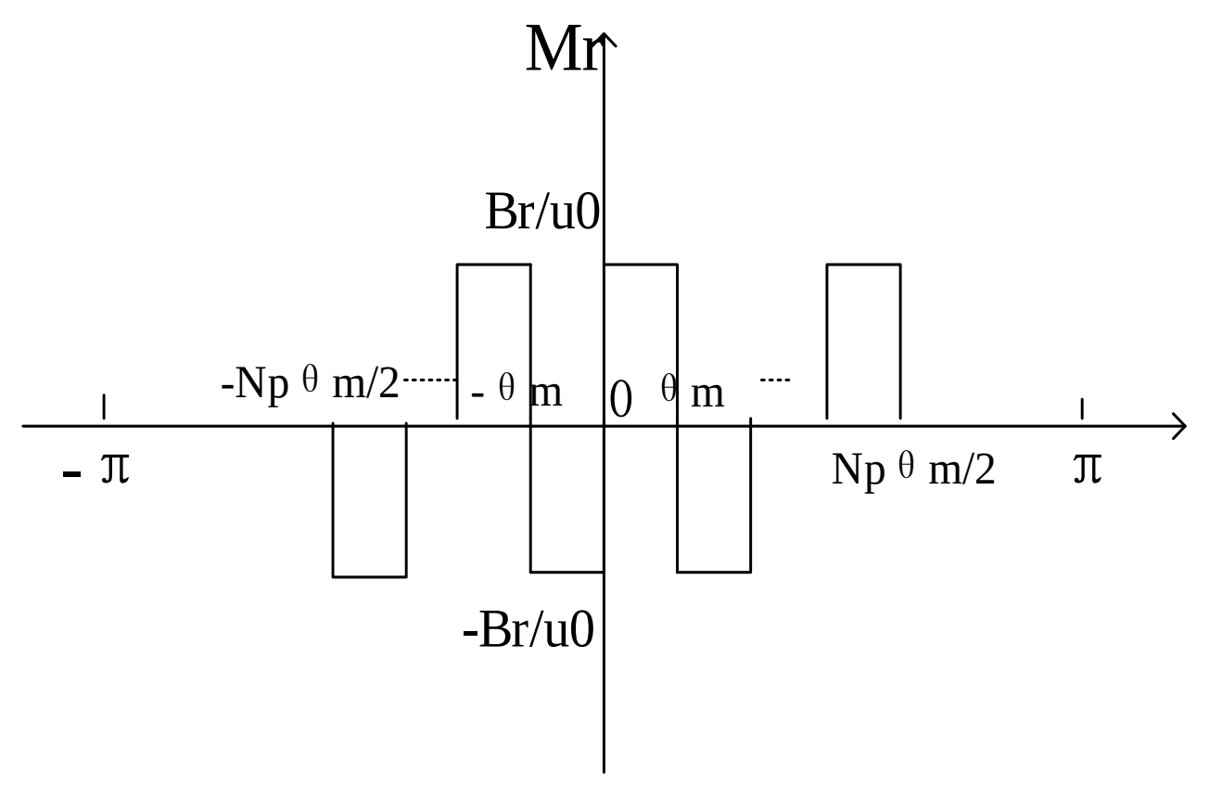
In Cartesian coordinates, the entire domain of the magnetic field is divided into 13 regions as shown in above picture.

Transformed model in Polar coordinates



In Polar coordinates, the number of subdomains decreased to the 6 regions which can reduce the computational complexity.

Magnetization distribution



$$\begin{cases} M_r(\theta_s)=M_r(\theta_s-\theta_{ms})=\sum\limits_{n=1}^{\infty}[M_{rcn}\cos(n\theta_s)+M_{rsn}\sin(n\theta_s)] \\ M_\theta(\theta_s)=M_\theta(\theta_s-\theta_{ms})=\sum\limits_{n=1}^{\infty}[M_{\theta cn}\cos(n\theta_s)+M_{\theta sn}\sin(n\theta_s)] \end{cases}$$

Boundary condition

$$\begin{cases} r=Rp:Br1=Br2 \\ r=Rp:H_{\theta 1}=H_{\theta 2} \end{cases}$$

$$\begin{cases} r=Rg:Br2=Br3(\theta_s\varepsilon(-\theta_3/2,\theta_3/2)) \\ r=Rg:H_{\theta 2}=H_{\theta 3}(\theta_s\varepsilon(-\theta_3/2,\theta_3/2)) \\ r=Rg:0(otherwise) \end{cases}$$

$$\begin{cases} r=Rs:Br3=Br5(\theta_s\varepsilon(-\theta_3/2,\theta_3/2)) \\ r=Rs:H_{\theta 3}=H_{\theta 5}(\theta_s\varepsilon(-\theta_3/2,\theta_3/2)) \\ r=Rs:0(otherwise) \end{cases}$$

$$\begin{cases} r=Rg:Br2=Br4(\theta_s\varepsilon(\pi-\theta_4/2,\pi+\theta_4/2)) \\ r=Rg:H_{\theta 2}=H_{\theta 4}(\theta_s\varepsilon(\pi-\theta_4/2,\pi+\theta_4/2)) \\ r=Rg:0(otherwise) \end{cases}$$

$$\begin{cases} r=Rs:Br_4=Br_5(\theta_s\varepsilon(\pi-\theta_4/2,\pi+\theta_4/2)) \\ r=Rs:H_{\theta 4}=H_{\theta 5}(\theta_s\varepsilon(\pi-\theta_4/2,\pi+\theta_4/2)) \\ r=Rs:0(otherwise) \end{cases}$$

Magnetic field anlysis

The exact analytical solutions in various regions are determined by applying the boundary and interface conditions. the coefficient equation is as follows:

Interface between Air-gap(region1) and segment (region2):

$$\begin{cases} A_1(1+G1^2)-A_2G_2-B_2 \\ =-u_0/n^2-1[(nR_rG_1+R_p)M_{\theta cn}-(R_mG_1+nR_p)M_{rsn}] \\ C_1(1+G1^2)-C_2G_2-D_2 \\ =-u_0/n^2-1[(nR_mG_1+R_p)M_{\theta sn}-(R_mG_1+nR_p)M_{rcn}] \\ A_1(1-G_1{}^2)/u_r-A_2G_2+B_2 \\ =-u_0/u_r(n^2-1)[n(R_m-R_rG_1)M_{\theta cn}-(R_m-R_rG_1)M_{rsn}] \\ C_1(1-G_1{}^2)/u_r-C_2G_2+D_2 \\ =-u_0/u_r(n^2-1)[n(R_m-R_rG_1)M_{\theta sn}-(R_m-R_rG_1)M_{rcn}] \end{cases}$$

Interface between Air-gap(region2) and segment (region3):

$$\begin{cases} -A_2(n/R_g)+B_2(n/R_g)(R_p/R_g)^n \\ =A_3f_k(R_g)\varsigma+B_3g_k(R_g)\eta \\ -C_2(n/R_g)+D_2(n/R_g)(R_p/R_g)^n \\ =A_3f_k(R_g)\varsigma+B_3g_k(R_g)\eta \\ A_3(R_g/R_s)^{k\pi/\theta_2}+B_3(R_g/R_g)^{-k\pi/\theta_2}=F_{2k} \end{cases}$$

$$\begin{cases} F_{2k}=\sum\limits_{n=1}^{\infty}(A_2(R_g/R_g)^n+B_2(R_g/R_r)^{-n})2\pi/\theta_2\varsigma \\ +\sum\limits_{n=1}^{\infty}(C_2(R_g/R_g)^n+D_2(R_g/R_r)^{-n})2\pi/\theta_2\eta \\ F_{2k}{}^4=\sum\limits_{n=1}^{\infty}(A_2(R_g/R_g)^n+B_2(R_g/R_r)^{-n})2\pi/\theta_2\varsigma^4 \\ +\sum\limits_{n=1}^{\infty}(C_2(R_g/R_g)^n+D_2(R_g/R_r)^{-n})2\pi/\theta_2\eta^4 \end{cases}$$

Interface between Air-gap(region2) and end region (region4):

$$\begin{cases} -A_2(n/R_g)+B_2(n/R_g)(R_p/R_g)^n \\ =A_4f_k(R_g)\varsigma^4+B_4g_k(R_g)\eta^4 \\ -C_2(n/R_g)+D_2(n/R_g)(R_p/R_g)^n \\ =A_4f_k(R_g)\varsigma^4+B_4g_k(R_g)\eta^4 \\ A_4(R_g/R_s)^{k\pi/\theta_2}+B_4(R_g/R_g)^{-k\pi/\theta_2}=F_{2k}{}^4 \end{cases}$$

Interface between end region (region3) and Air (region5):

$$\begin{cases} A_3f_k(R_s)+B_3g_k(R_s)]\varsigma=B_5n/R_s \\ A_3f_k(R_s)+B_3g_k(R_s)]\eta=D_5n/R_s \\ A_5+B_5(R_s/R_g)^{k\pi/\theta_3}=F_{5k} \end{cases}$$

Interface between end region (region4) and Air (region5):

$$\begin{cases} A_5f_k(R_s)+B_5g_k(R_s)]\varsigma^4=B_4n/R_s \\ A_5f_k(R_s)+B_5g_k(R_s)]\eta^4=D_4n/R_s \\ A_5+B_5(R_s/R_g)^{k\pi/\theta_3}=F_{5k}{}^4 \end{cases}$$

$$\begin{cases} F_{5k}=\sum\limits_{n=1}^{\infty}(B_3(R_s/R_s)^{-n})2\pi/\theta_3\varsigma \\ +\sum\limits_{n=1}^{\infty}(D_3(R_s/R_g)^{-n})2\pi/\theta_3\eta \\ F_{5k}{}^4=\sum\limits_{n=1}^{\infty}(B_3(R_s/R_s)^{-n})2\pi/\theta_3\varsigma^4 \\ +\sum\limits_{n=1}^{\infty}(D_3(R_s/R_g)^{-n})2\pi/\theta_3\eta^4 \end{cases}$$

Analysis result

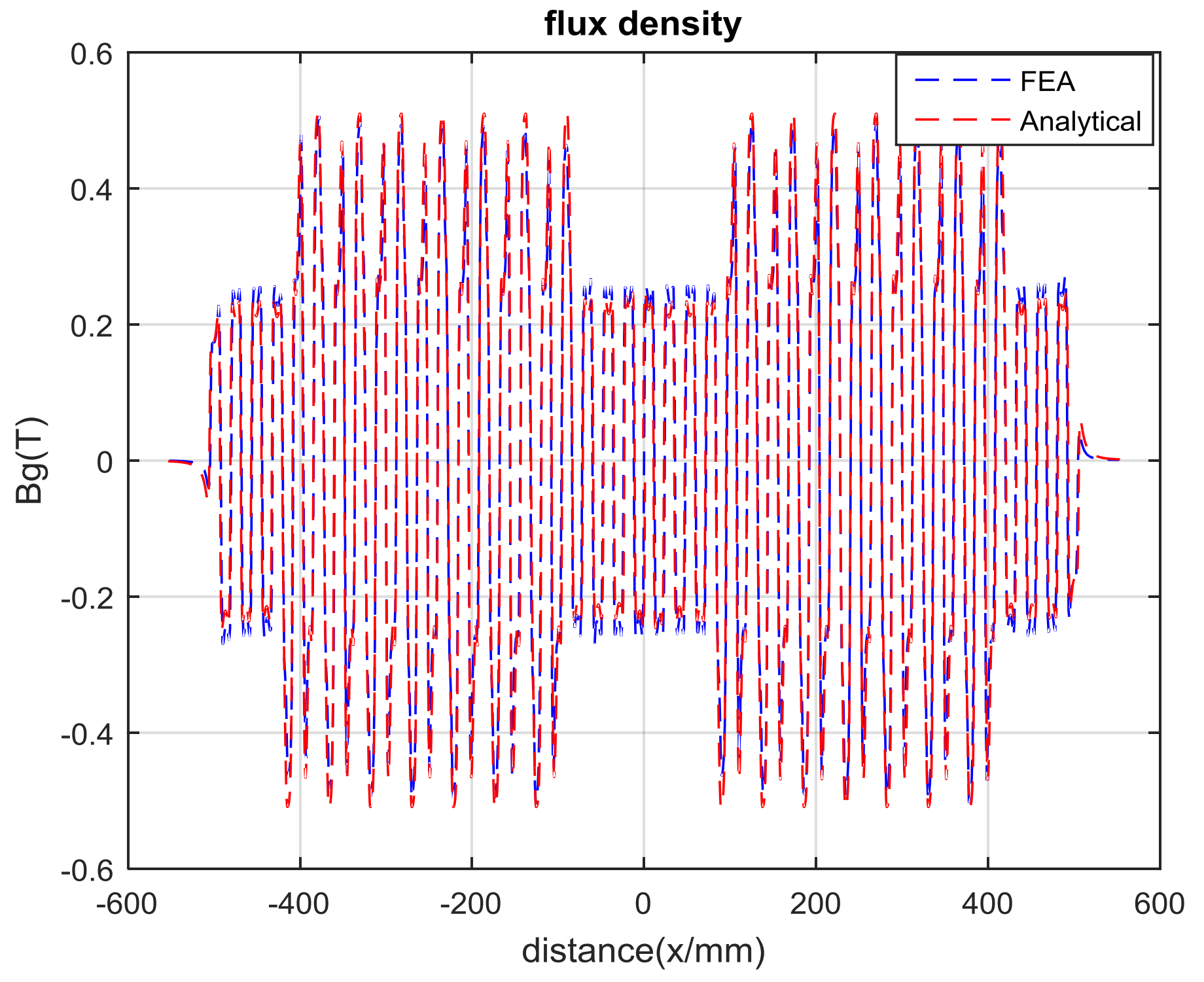
Main prameters of PS-PMLSM

Table

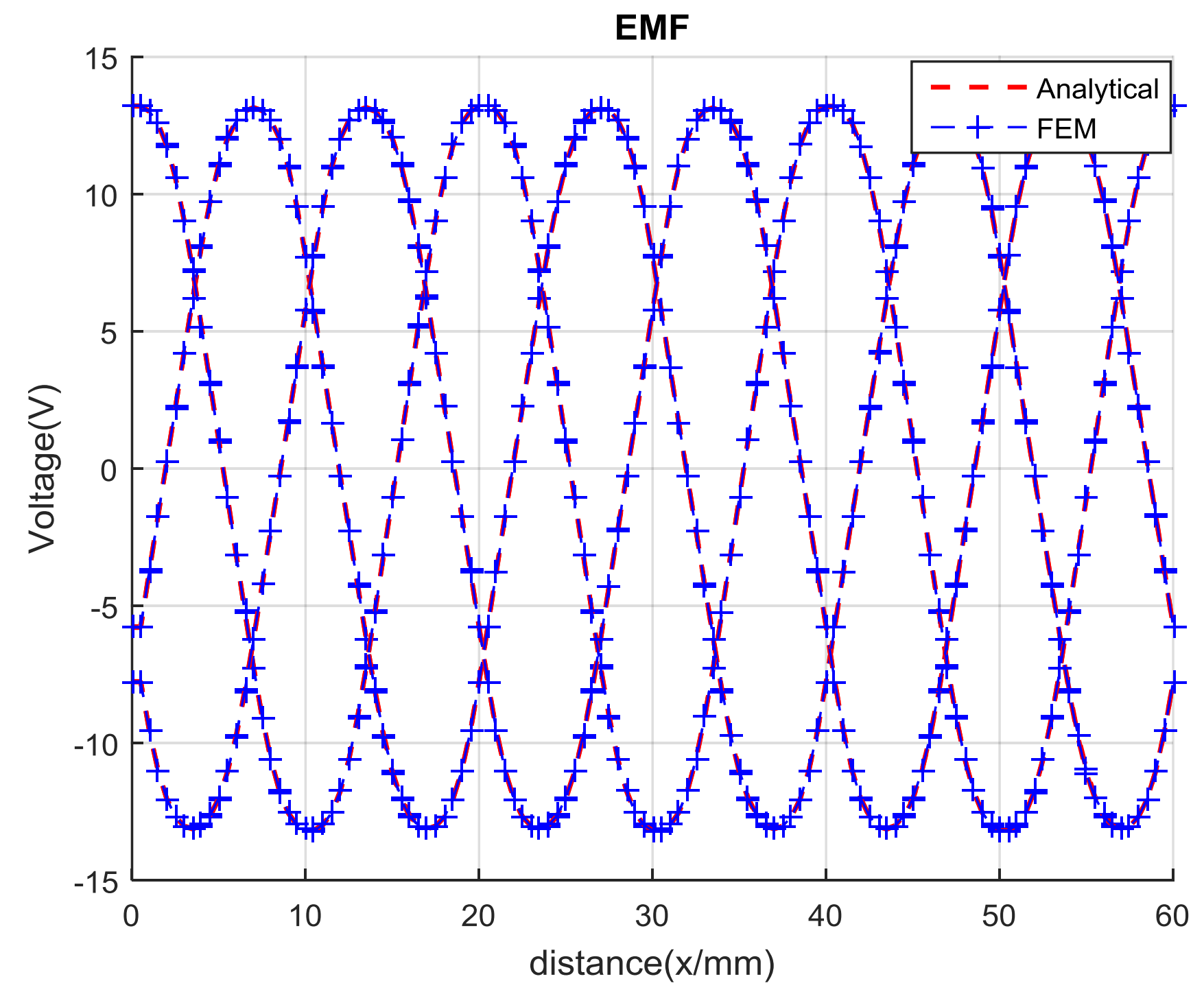
Symbol	Parameters	Value
Ls_1	Axial length of primary	336 mm
hs	Height of stator	16 mm
g	Length of air-gap	2 mm
hm	Thickness of permanent magnet	1.5mm
Lm	Length of permanent magnet	12 mm
Ws	Slot width	10 mm
Wd	Slot depth	30mm
Ur	Relative Permeability	1.09T
Br	Remanence of PM	1.27T

The main parameters of PS-PMLSM, which are used for validation, are given in Table .

Distribution of Flux denstiy



Distribution of Back-EMF



The distribution of magnetic flux density and Back-EMF are plotted. Through the comparison, the analytical results are in good consistent with the simulation results, the flux density of air-gap in slot region is about 0.55T, in three end regions are about 0.25T, the maximum value of the EMF is about 14V.