[VP11-10] Performance Analysis of Single-Phase Inverter-Fed Permanent Magnet Synchronous Motor with Ladder-Connected Winding

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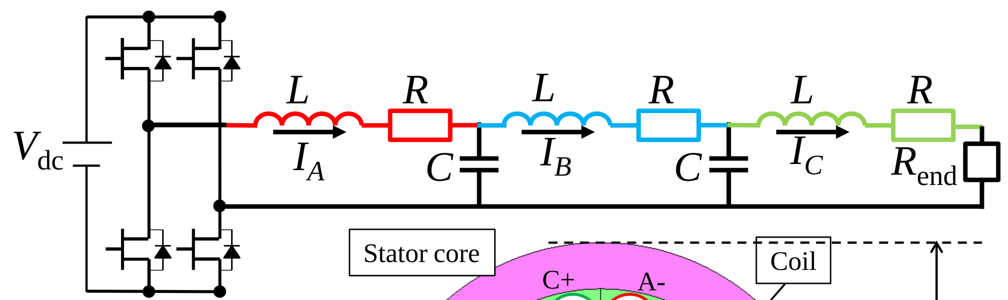
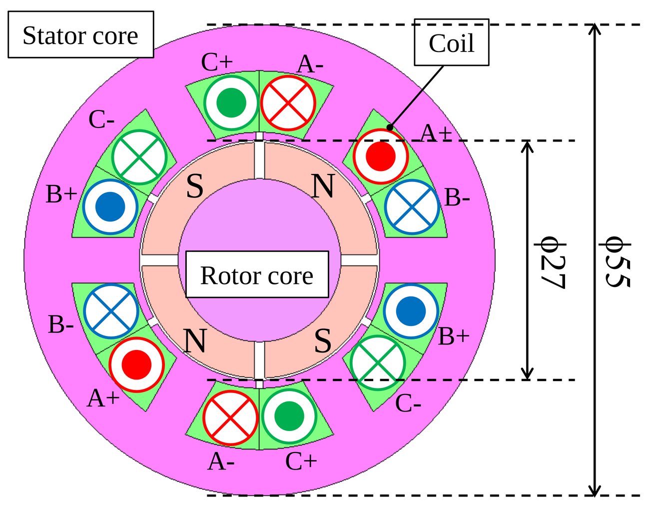
Introduction

The authors focused on a nonlinear LC ladder circuit, which is a type of distributed-element circuit, for fewer number of the switching device. The LC ladder circuit is able to excite special nonlinear wave phenomena such as intrinsic localized modes or magnetic solitons (Kato, *IEEE Trans. Magn.*, 2022).
In these phenomena, waves of magnetic energy propagate along the LC ladder circuit, which looks like rotating magnetic field.
This study proposes a new permanent magnet synchronous motor (PMSM) driven by the single-phase H-bridge inverter.
First, a basic configuration and mathematical model are presented. Second, the feasibility of the proposed PMSM is validated through phase current and torque characteristics.

PMSM with Ladder-Connected Winding

Basic configuration





The stator and rotor structures are the same as a conventional 4p6s PMSM with concentrated winding. The general PMSM connects the three coils in a delta- or star-like configuration, while the proposed PMSM connects the three coils in a ladder-like configuration by using two capacitors and one resistor at the end. A single-phase AC current is supplied from a terminal by the H-bridge inverter.
The AC current propagates along the LC ladder circuit like a wave because this LC ladder network is equivalent to a distributed-element model such as a transmission line [4]. Besides the wave propagation effect, an intrinsic LC filter effect is useful for eliminating a harmonic current associated with a carrier frequency of pulse width modulation (PWM) control, resulting in reduced iron loss and acoustic noise.

Mathematical modeling

- Rotor pole saliency is negligible
- Space harmonics of PM flux linkage is zero
- Time harmonics of phase current is zero
- Phase inductance is independent of both a rotor angle and phase current (no saturation)

Kirchhoff's voltage law gives the following voltage equations for the three different loops:

$$\begin{aligned} V_{\rm in} - V_a &= RI_a + L\frac{dI_a}{dt} + M\frac{dI_b}{dt} + M\frac{dI_c}{dt} + \frac{d\psi_a}{dt}, \\ V_a - V_b &= RI_b + L\frac{dI_b}{dt} + M\frac{dI_c}{dt} + M\frac{dI_a}{dt} + \frac{d\psi_b}{dt}, \\ V_b &= (R+R_{\rm end})I_c + L\frac{dI_c}{dt} + M\frac{dI_a}{dt} + M\frac{dI_b}{dt} + \frac{d\psi_c}{dt}, \end{aligned} \quad (1)$$

where V_a and V_b are the voltage drop across the first and second capacitors, respectively. Kirchhoff's current law gives the following current equations for the two different nodes:

$$\begin{aligned} I_a &= I_b + C\frac{dV_a}{dt}, \\ I_b &= I_c + C\frac{dV_b}{dt}. \end{aligned} \quad (2)$$

Based on the above assumption, Phasor representation ($d/dt = j\omega$) is introduced to evaluate static response of the PMSM, where j is the imaginary unit and ω is the rotational speed of the rotor. The phase current $\boldsymbol{I} = (I_a, I_b, I_c)$ is calculated by the following equation:

$$\boldsymbol{I} = \left(\boldsymbol{Z} - \omega^2\boldsymbol{X} + j\omega\boldsymbol{Y}\right)^{-1} j\omega \boldsymbol{V_{in}} e^{j\omega t} \quad (3)$$

where $[\boldsymbol{Z} - \omega^2\boldsymbol{X} + j\omega\boldsymbol{Y}]$ is the impedance matrix derived from Eqs. (1) and (2). A motor torque T is calculated by the cross product

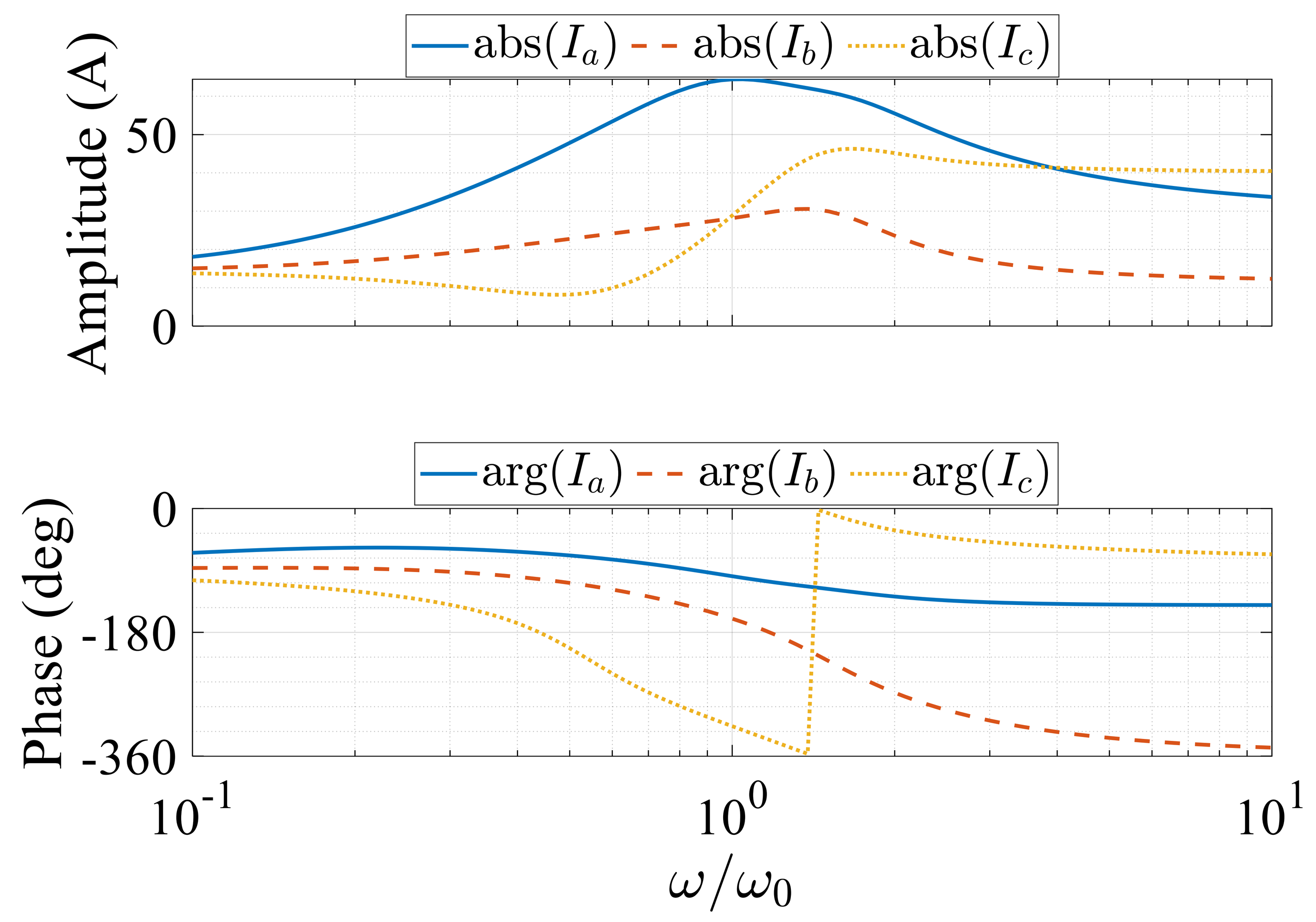
$$T = \boldsymbol{I} \times \boldsymbol{\psi} \quad (4)$$

Performance Evaluation

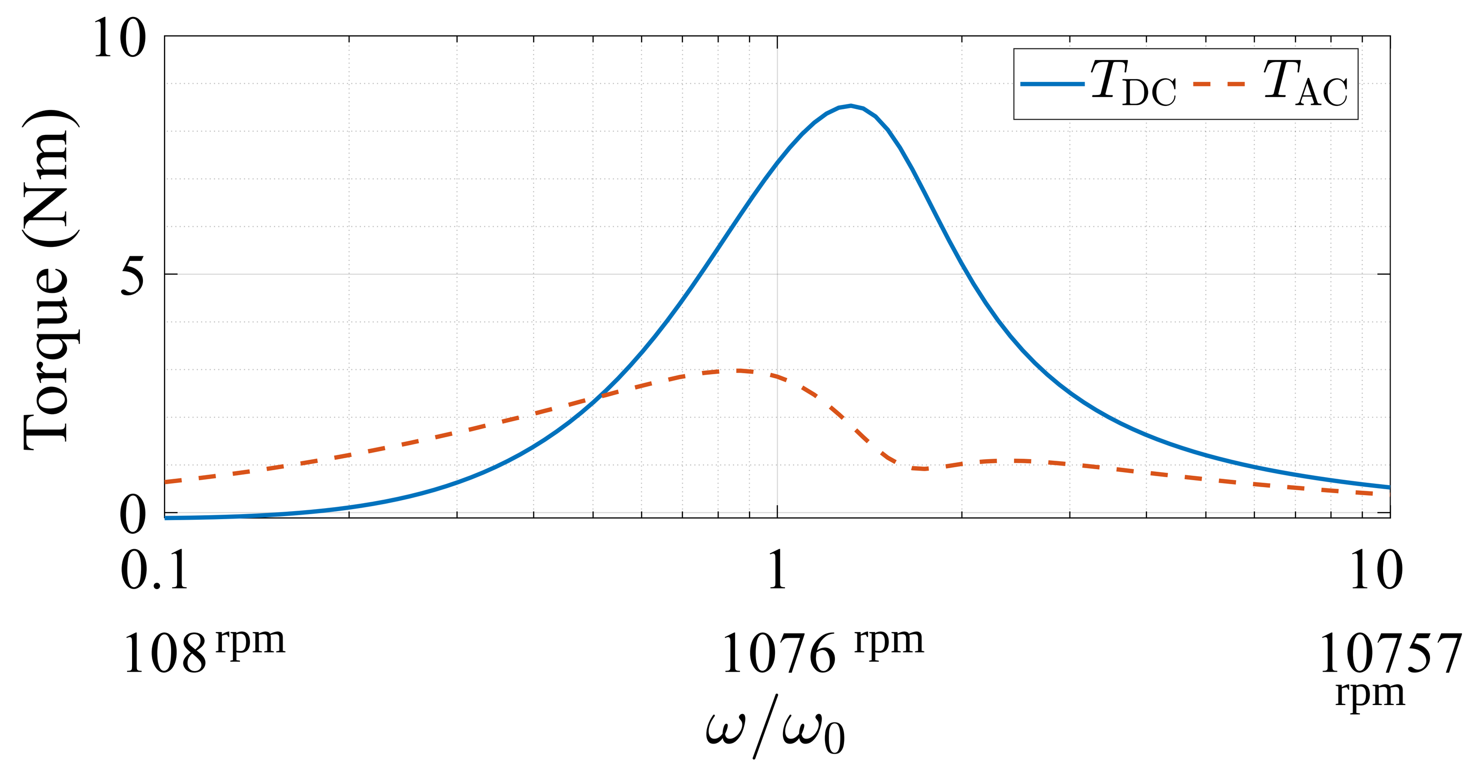
Motor specification

Parameter (Unit)	Symbol	Value
Phase inductance (mH)	L	1.97
Mutual inductance (mH)	M	-0.96
Capacitance (mF)	C	10
Normalized angular frequency (rad/s)	ω_0	225.3
Phase resistance (Ω)	R	0.7
Termination resistance (Ω)	$R_{\rm end}$	0.7
PM flux linkage (mWb)	ψ	67
Input voltage (V)	$V_{\rm in}$	$40\cos(\omega t)$
Relative permeability of the cores (-)	μ_r	1000 (Linear material)

Frequency response of phase current



Frequency response of phase current



Due to the complicated phase current characteristics above, the torque strongly depends on the frequency ω (i.e.,rotational speed).
Although the current and torque characteristics are still difficult to control, the validity of the proposed PMSM is clarified from the above figures.

Conclusion and Future Works

- **This study proposed a new permanent magnet synchronous motor (PMSM) driven by the single-phase H-bridge inverter. Ladder-connected winding propagated phase current supplied by a sing-phase AC current source.**
- **Mathematical modeling is presented. Phase current and torque characteristics were investigated numerically.**
- **Although the current and torque characteristics are still difficult to control, the feasibility of the proposed PMSM was validated.**

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