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Linear Machines, Electromagnetic Actuators and Applications
BD-08

Numerical Analysis of Magnetic Soliton Excited on Nonlinear LC Ladder Circuit Array Using Permanent Magnet Flux Biased Inductor

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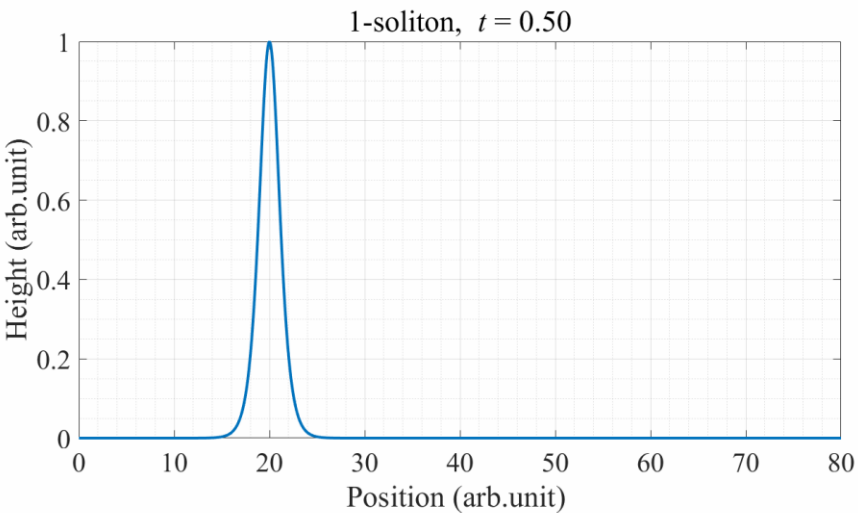
Outline

- **Introduction**
  - Nonlinear wave phenomena and soliton
  - Soliton observed in the discrete system (LC ladder circuit array)
  - Final goal and achievement of this study
- **Magnetic Soliton Using Permanent Magnet Flux Biased Inductor**
  - Basic structure and operational principle
  - Exponential inductance characteristics through 2-D FEA
  - Design strategy for cancelling PM bias flux
  - Excitation of magnetic soliton through numerical simulation
- **Conclusion and Future Works**

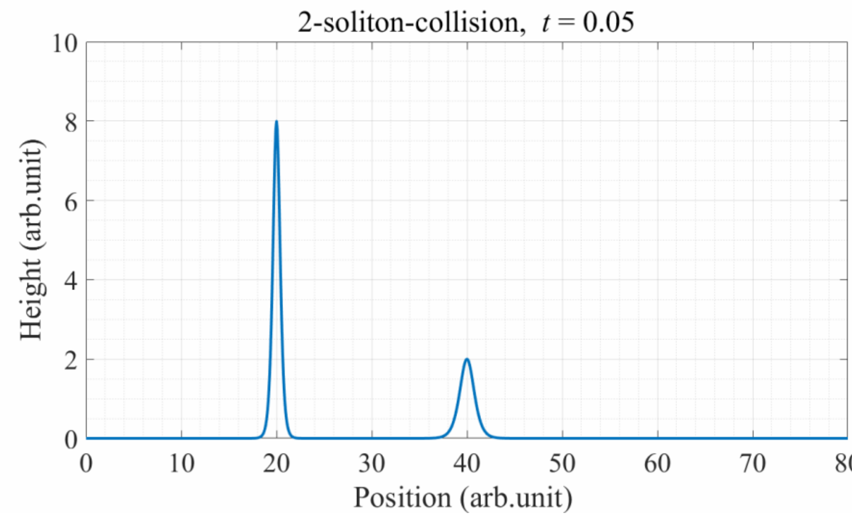
Background ~What Is Soliton ?~

Soliton = Solitary wave＋ on (a prefix representing the nature of a particle)
「A pulsed wave that maintains its shape and constant velocity」

Motion of one soliton



Overtake and collision of two solitons



Feature 1
Unchanged shape and velocity
（Correspond to "the law of inertia"）

Feature 2
Stable before and after collision
（Correspond to "conservation of momentum"）

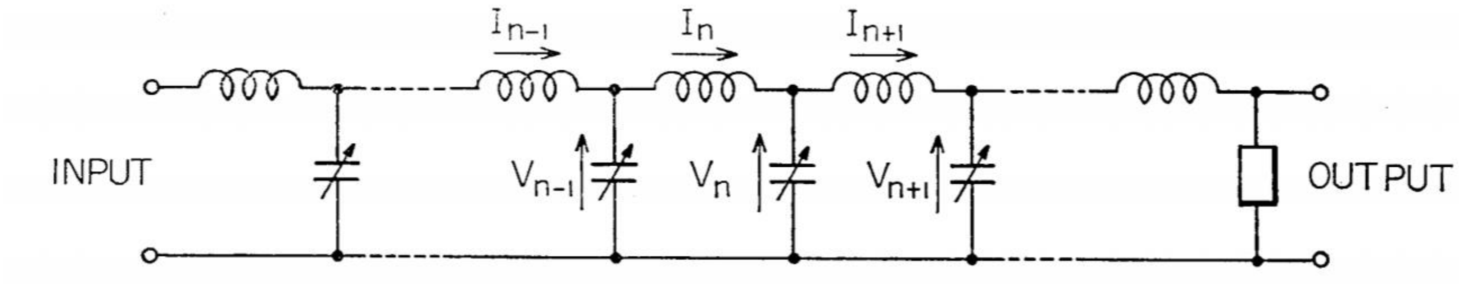
- Much attention have been paid to unique behaviors of the soliton
- The soliton has been observed in various nonlinear systems (fluid, optics, polymer chemistry, and **electrical circuit**)

Soliton in Discrete System (Circuit)

- Soliton was excited experimentally on a nonlinear LC ladder circuit array

→ **Linear inductors** and **nonlinear capacitors** are interconnected like **a ladder**

Configuration



Nonlinear capacitance

$$Q = C(V)V = aV^{-b} * V = aV^{1-b}$$

exponentiation

Loop equation of *n*th LC loop

$$L\ddot{Q}_n = \pm V_0 \left[\left(e^{\pm \frac{Q_{n-1}}{Q_0}} \right) + \left(e^{\pm \frac{Q_{n+1}}{Q_0}} \right) - 2 \left(e^{\pm \frac{Q_n}{Q_0}} \right) \right]$$

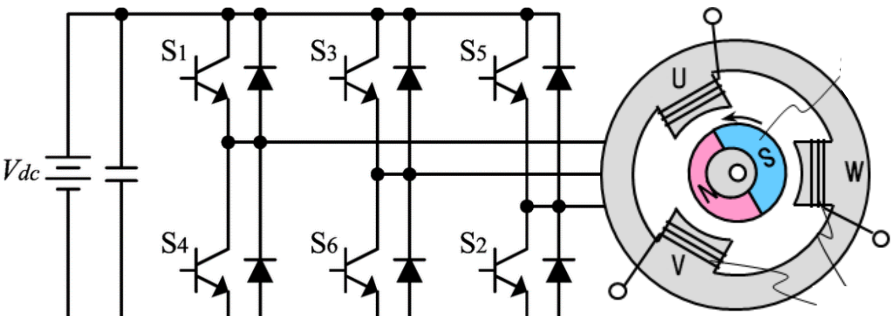
= soliton solution

- Rotating magnetic field is generated if the ladder circuit is connected annularly
- Magnetic soliton is excited when using magnetic saturation of iron core effectively

[1]: Ryogo Hirota, "Studies on Lattice Solitons by Using Electrical Networks," J. Phys. Soc. Japan, 28 (1970) pp. 1366-1367

Final Goal and Achievement

Typical AC motors

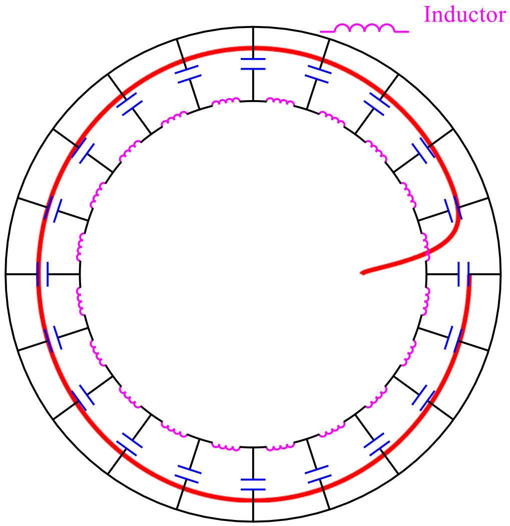


3-phase PWM inverter

3-phase AC Motor

- Current: switched by power transistors
- Design: integrated system (inverter and motor)

Magnetic soliton motor



- Current: transmit as **a wave**
- Design: integrated system (**simpler inverter** and motor with a function of rotating magnetic field)

Final goal

- Propose a new AC motor driven by nonlinear wave phenomena (soliton)

Achievement of this study

- Excitation of a magnetic soliton by a permanent magnet flux biased inductor
- Generation of rotating magnetic field by the magnetic soliton

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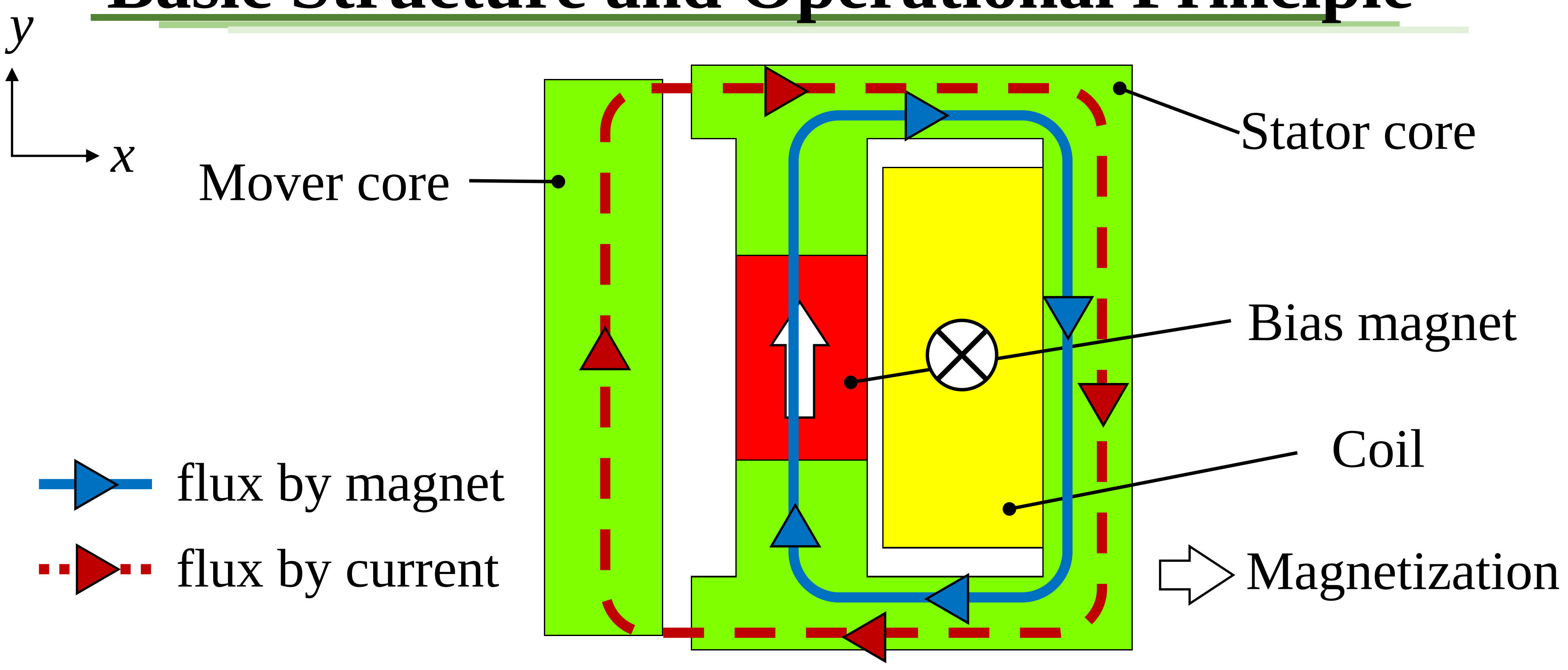
Basic Structure and Operational Principle

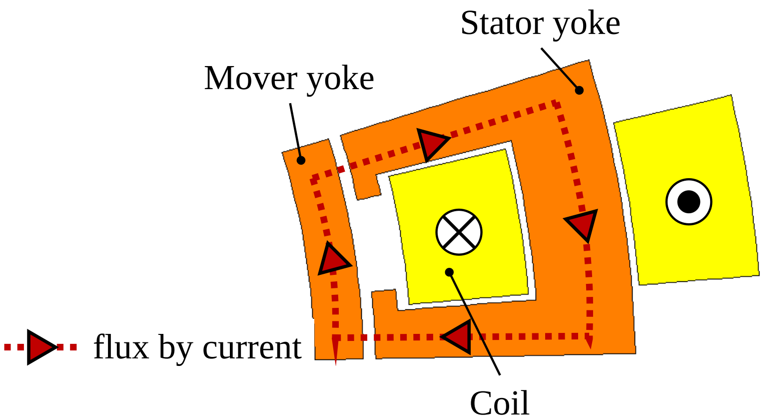


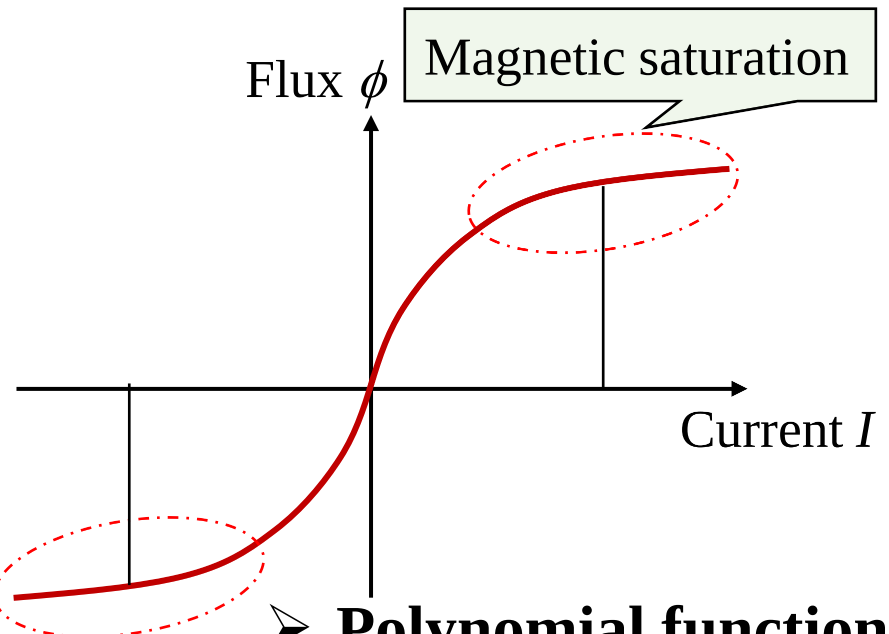
Permanent-magnet-flux-biased (PMFB) inductor

- Bias flux by PM flows mainly through the stator core because of the **air-gap** → shifts the operational point of the *B*-*H* curve
- Applying positive and negative current makes different (low and high) inductance characteristics, respectively

Comparison of Operational Principle

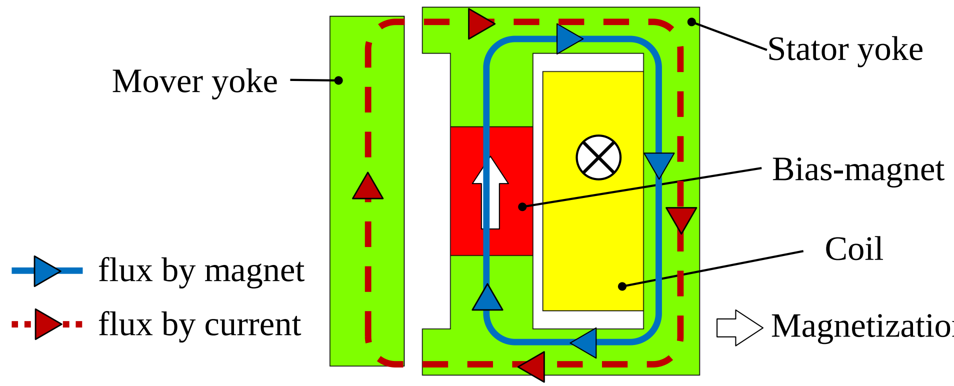
Nonlinear inductor without PM

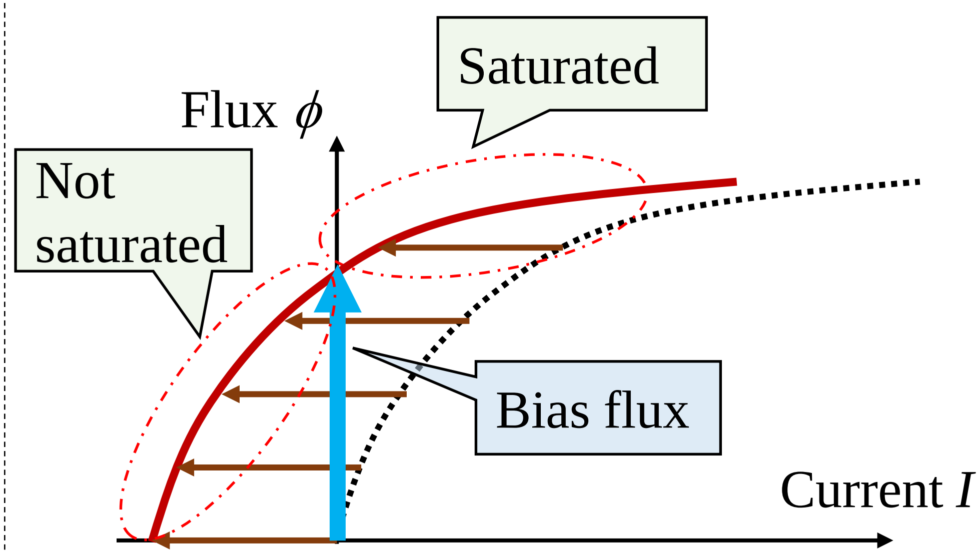




➢ **Polynomial function**

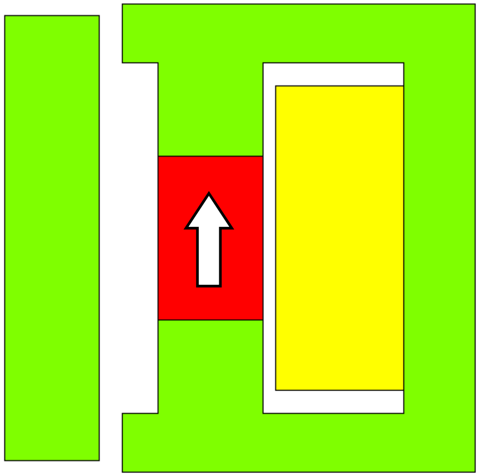
PMFB inductor



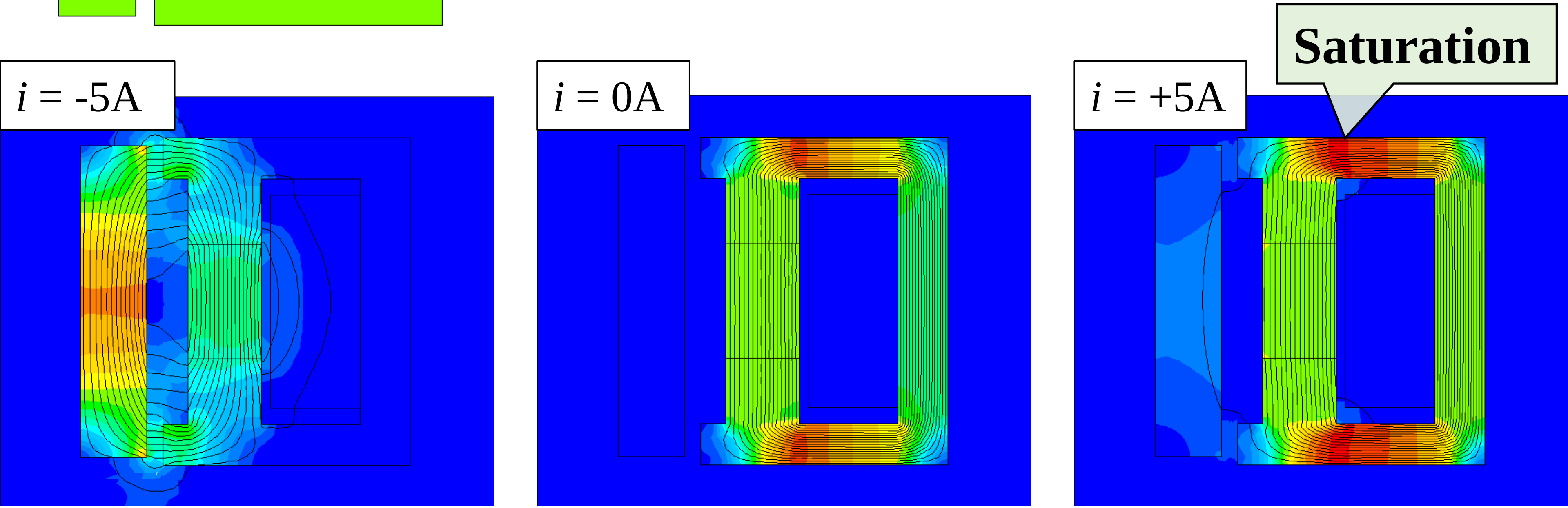


➢ **Exponential function**

FEA Results

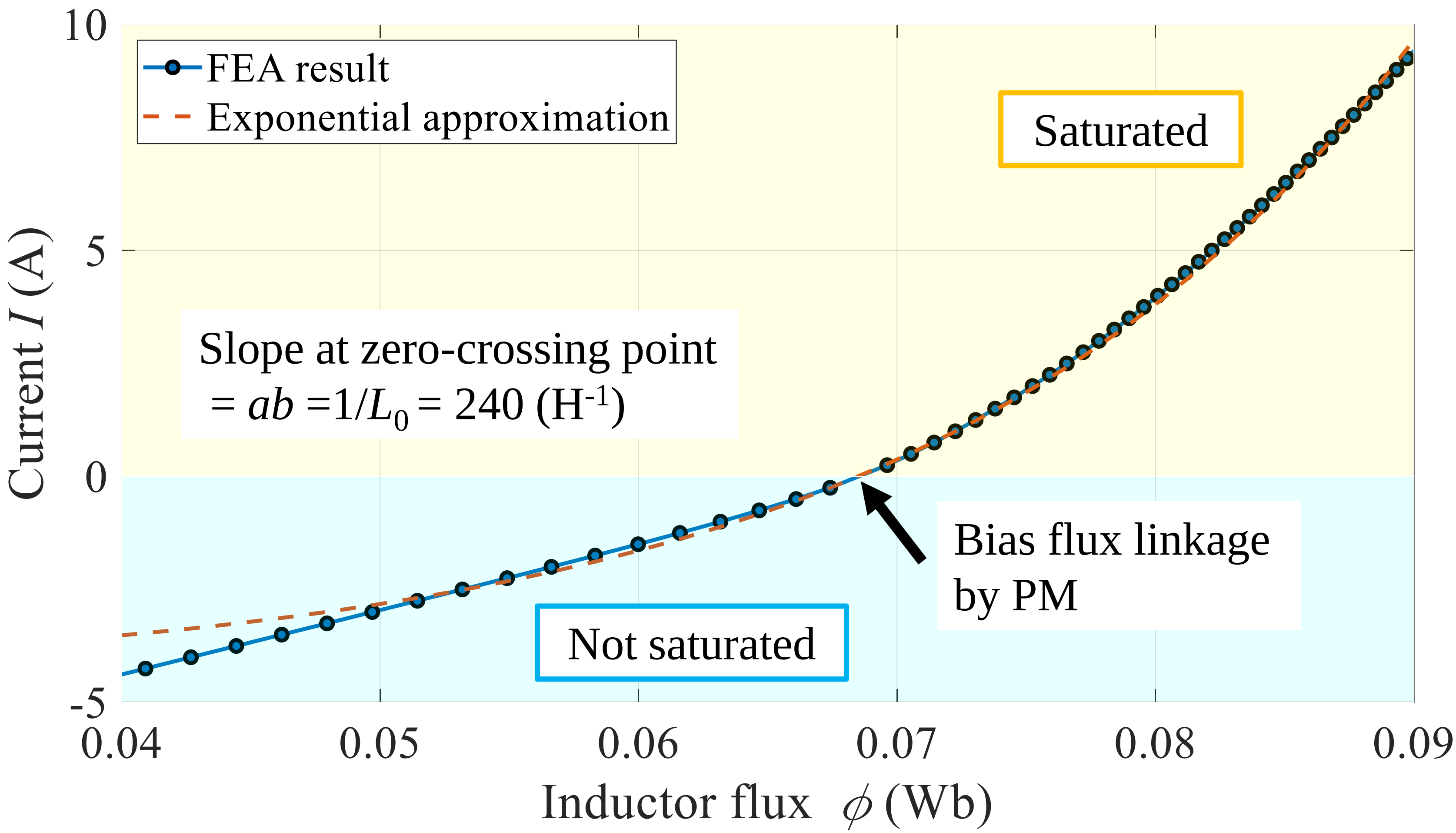


Inductance characteristic is calculated through electromagnetic field analysis employing 2-D axisymmetric finite element method



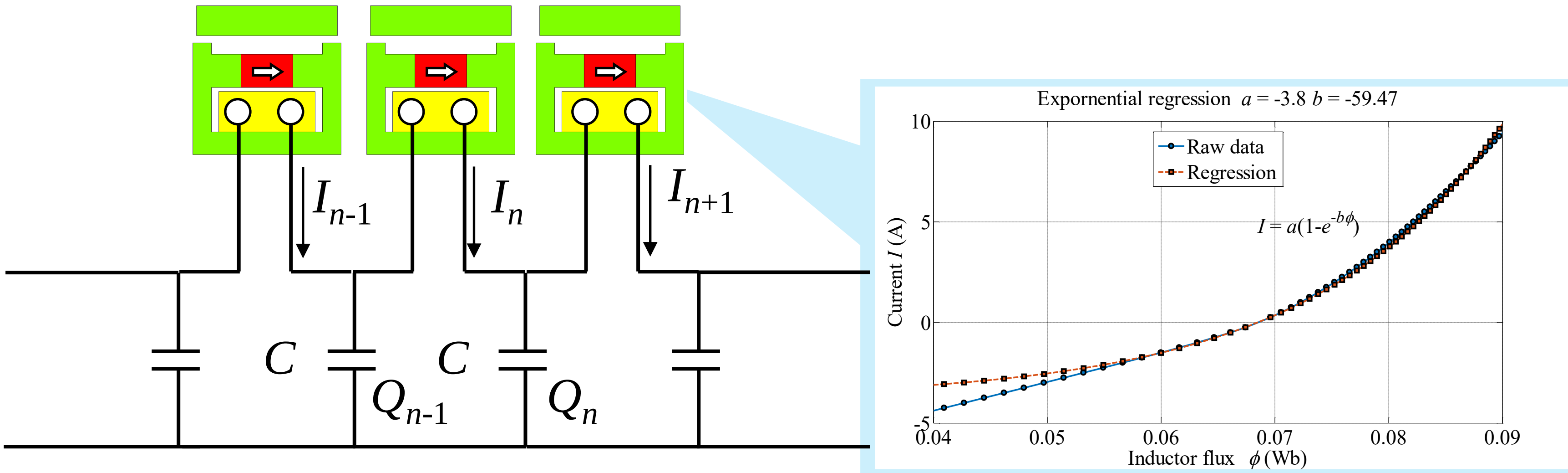
➢ Magnetic saturation occurs only when inductor current is positive

Exponential Inductance Characteristic



➢ Proposed inductor has exponential property of inductance

Magnetic Soliton Excited on LC Circuit



Exponential inductance $I_n = a\left(1 - e^{-b(\phi_n - \phi_{PM})}\right)$

ϕ_{PM}: Bias flux by PM

Loop equation of
*n*th LC loop

$$\frac{d^2\phi_n}{dt^2} = \frac{a}{C}\left(2e^{-b\phi_n} - e^{-b\phi_{n-1}} - e^{-b\phi_{n+1}}\right)$$

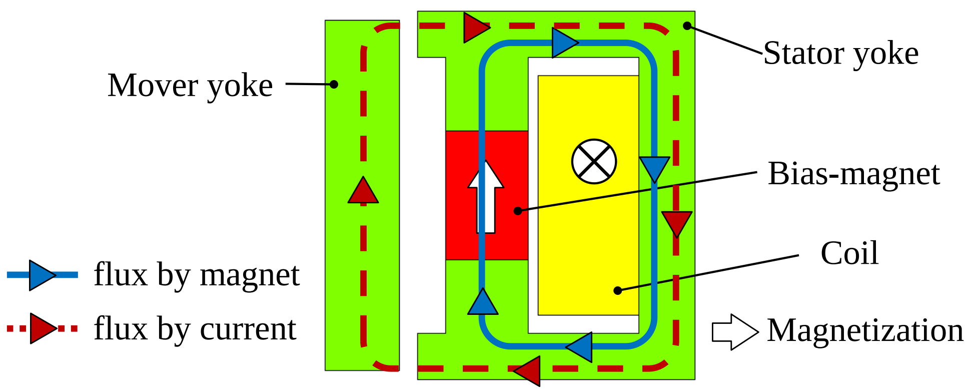
Toda lattice equation
(Known for having soliton)

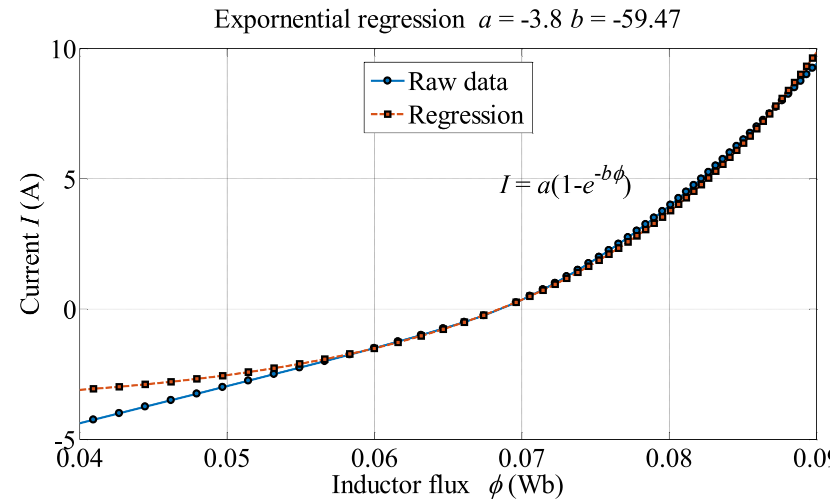
$$\frac{d^2 r_n}{dt^2} = \frac{a}{m}\left(2e^{-br_n} - e^{-br_{n-1}} - e^{-br_{n+1}}\right)$$

Same form

- Proposed LC circuit has soliton solutions (pulsed magnetic flux wave)

Numerical Simulation Condition





$$I_n = a\left(1 - e^{-b(\phi_n - \phi_{PM})}\right)$$

a= -4.5

b = -53.3 (H^{-1})

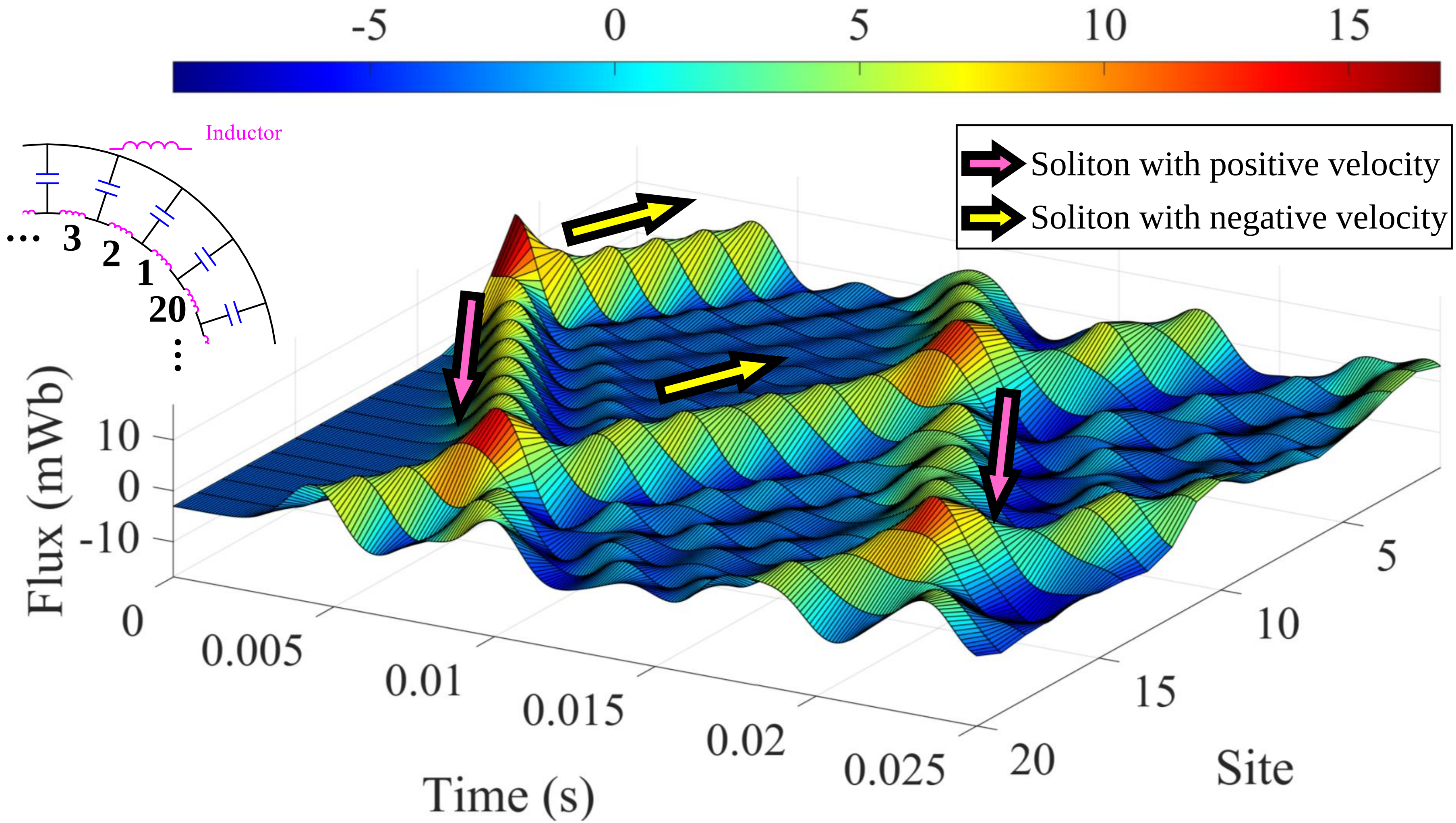
ϕ_{PM} =68.5 (mWb)

Simulation condition

Parameter	Symbol	Value
Capacitance (μF)	C	100
Amplitude of flux at center (mWb)	α	24.4
Degree of spread	κ	1.0
Angular frequency (rad/s)	β	1820
Times step (μs)	-	50
Number of inductors	-	27
Number of step	-	500
Time elapsed (s)	-	2.3

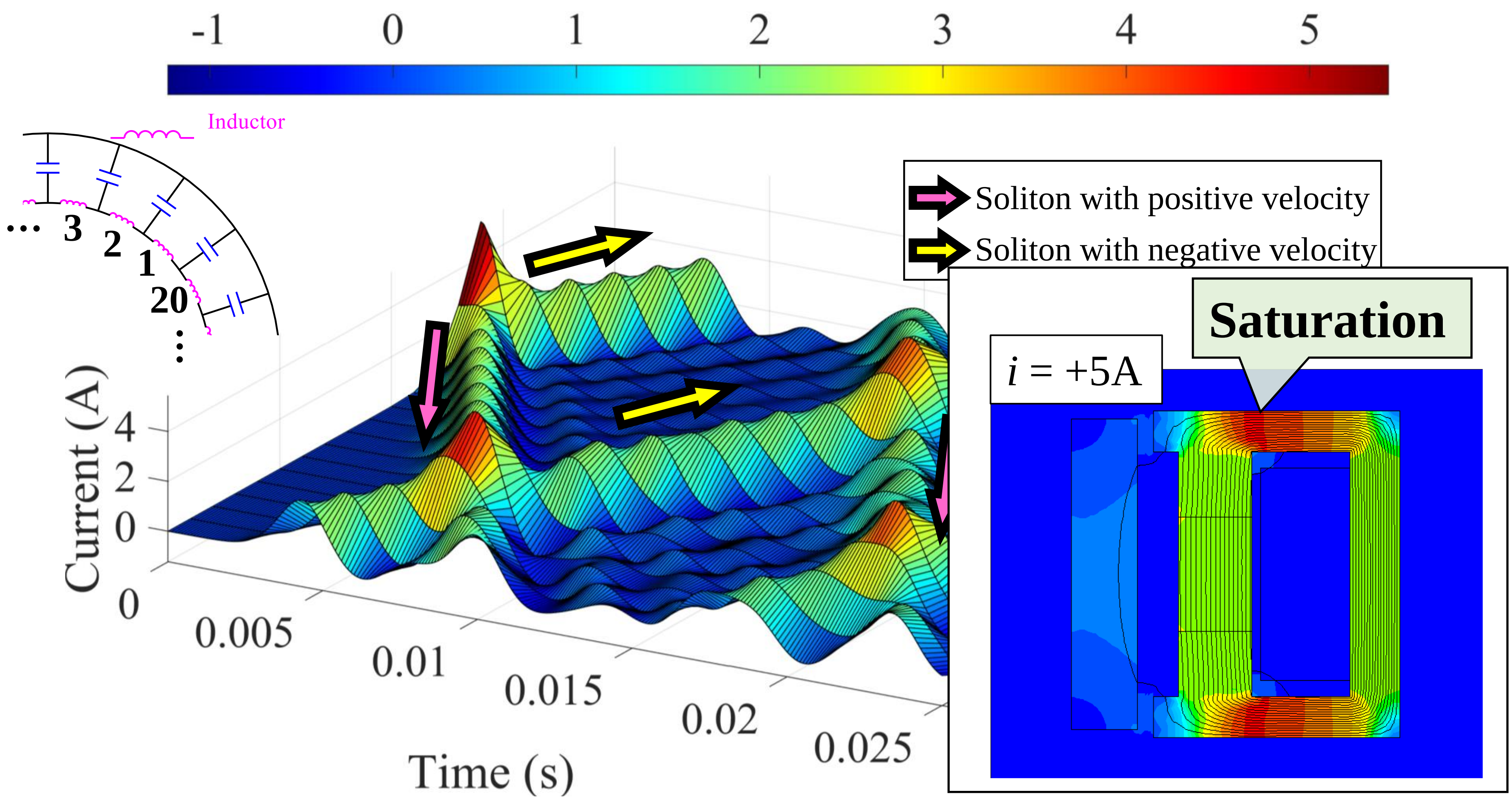
Time Evolution of Magnetic Soliton

- Initial magnetic flux at 0s was set so that one soliton can be excited



- Stable solitons remain for a long time without changing their shapes

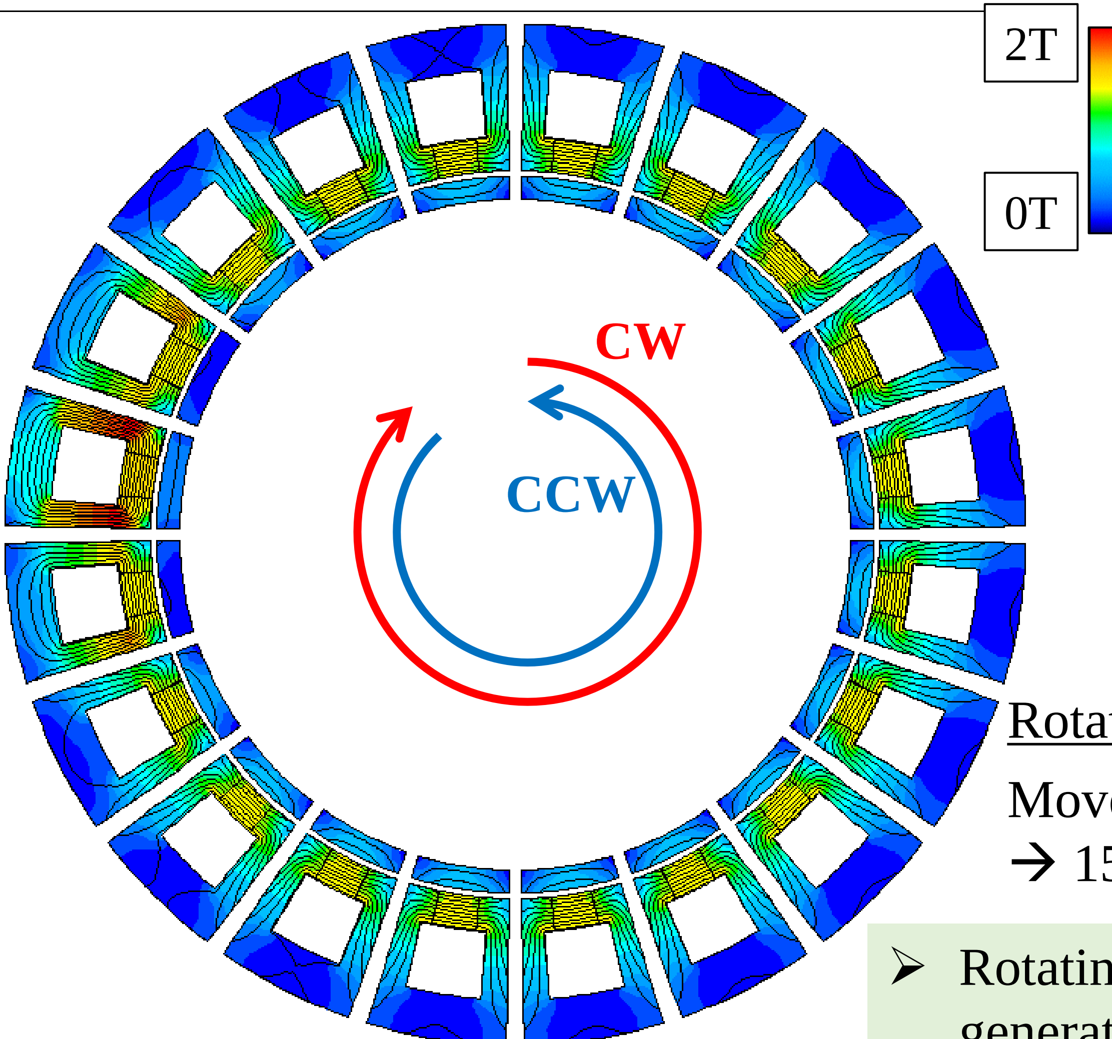
Time Evolution of Inductor Current

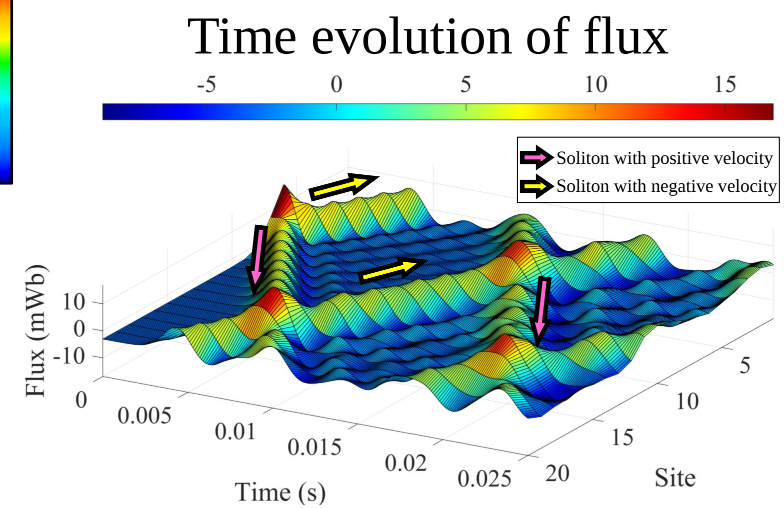


- Air-gap flux density is low because soliton uses saturated region
- Effective magnetic path is not formed

Flux Density Animation

※Circularized based on the structure of the PMFB inductor described before





<u>Rotational speed</u>

Moved across 10 LC arrays in about 0.7s
→ 15400 rpm

- Rotating magnetic field is successfully generated (low air-gap flux density)
- Single soliton was not obtained

Conclusion and Future Works

◆Permanent-magnet-flux-biased inductor

- Realized an **exponential inductance** characteristic due to the PM bias flux

◆LC ladder circuit array composed of PMFB inductors and capacitors

- Proved the **existence of a soliton solution** mathematically from the form of the loop equation
- Excited **two stable magnetic solitons** with different velocity through simulation
- Visualized **rotating magnetic field** with low air-gap flux density

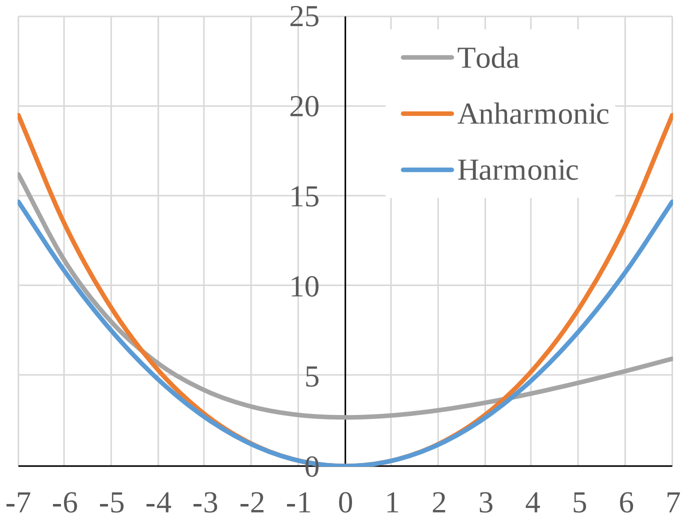
Wishful thinking

Magnetic soliton has a great potential to create new electromagnetic devices (Motors, actuators, and sensors).
Use of only single half-bridge inverter is expected to be enough for generation of rotating magnetic field, without using a conventional three-phase inverter.

- Structural development in magnetic circuit of PMFB
- Driver for supplying electrical energy into a decayed soliton
- Speed control of the rotating magnetic field

Toda Lattice and Soliton

Potential $\phi(r)$



Toda potential $$\varphi(r) = \frac{a}{b} e^{-br} + ar$$

Force $$f(r) = -\phi'(r) = a\left(e^{-br} - 1\right)$$

Toda lattice equation $$m\frac{d^2 r_n}{dt^2} = a\left(2e^{-br_n} - e^{-br_{n-1}} - e^{-br_{n+1}}\right)$$

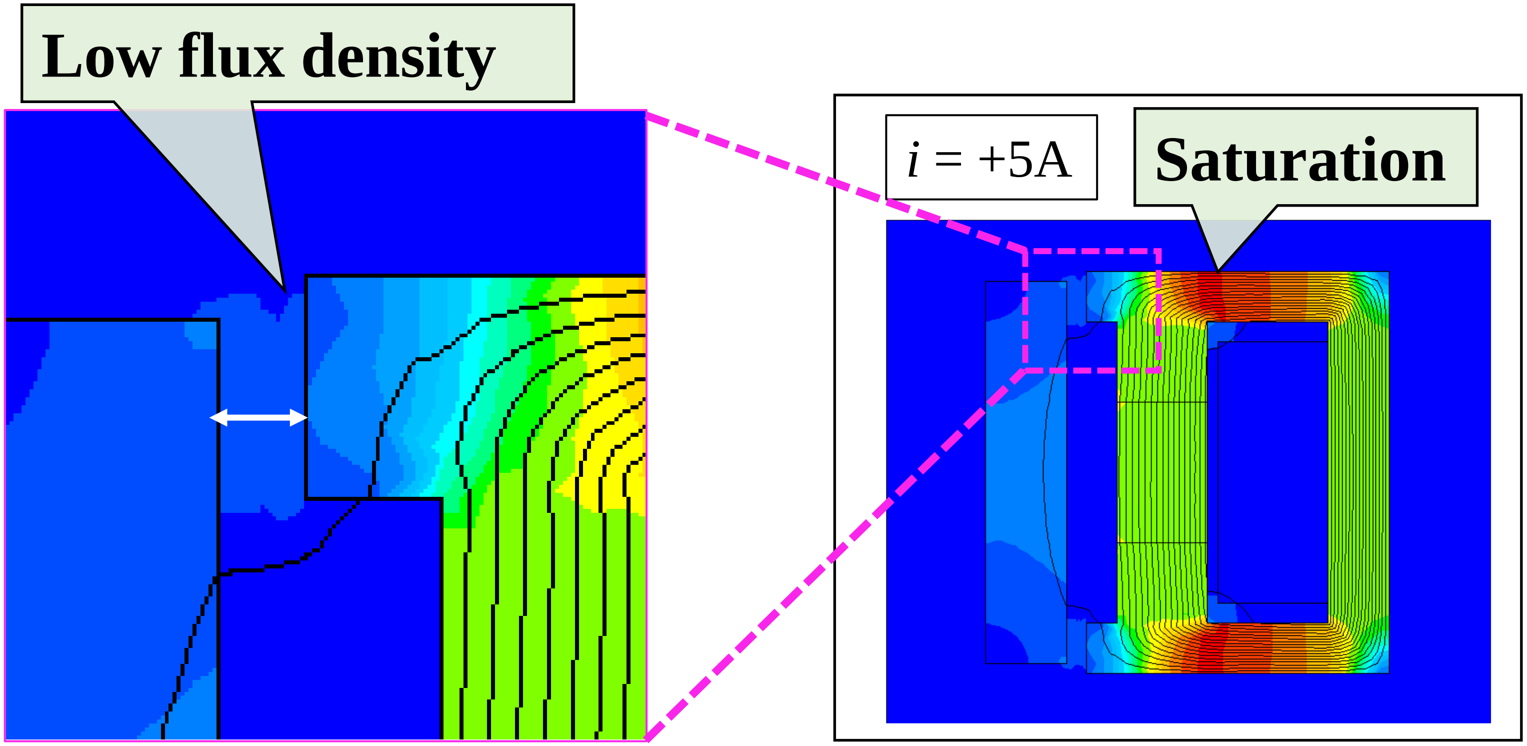
Solution $$r_n = y_{n+1} - y_n = \frac{-1}{b}\log\left(1 + \sinh^2\kappa \,\mathrm{sech}^2(\kappa n - \beta t + \delta)\right)$$

$$\beta = \pm\sqrt{\frac{ab}{m}}\sinh\kappa$$

➢ Toda lattice differential equation has a soliton solution

Ref：Morikazu Toda, ”Nonlinear oscillation and soliton”, NIPPON HYORON SHA, in Japanese

Air-gap flux density



- Air-gap flux density is **low** because the soliton uses **saturated region**
- Effective magnetic path is not formed
- Improved structure of inductor is necessary in order to allow more magnetic flux to pass through