# DEVELOPMENT OF A CURRENT TRANSFORMER MODEL WITH SATURATION CHARACTERISTICS

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USER SPOTLIGHT SERIES BY RTDS Technologies

# PRESENTATION CONTENTS

- **INTRODUCTION**

- **DEVELOPMENT OF A CT UDM (User Define Model)**
  - Purpose & Target CT Equivalent Circuit
  - Proposed  CT UDM
    - ✓ Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve
    - ✓ Dommel's network solution technique considering nonlinear circuit

- **SIMULATION STUDIES**
  - Verification of the CT UDM by applying open circuit test
  - Apply CT UDM to the power system

- **CONCLUSIONS**

# INTRODUCTION

## ❖ Background

- Distorted signals caused by CT saturation results in mal-operation or operating time delay of relay
- Many utilities, including KEPCO use real-time simulators such as RTDS to perform dynamic tests of relays on CT saturation
- Some CT saturation countermeasure algorithms use nonlinear magnetization characteristic curve of CT to cope with these problems
- Need to ensure correct relay operation by detecting CT saturation or restoring the distorted signals

## ❖ Problem

- When Vrms-Irms excitation curve (open circuit test data from a manufacturer) is applied to the RTDS CT model, the curve obtained from its simulation is a bit different from the applied Vrms-Irms data

# INTRODUCTION

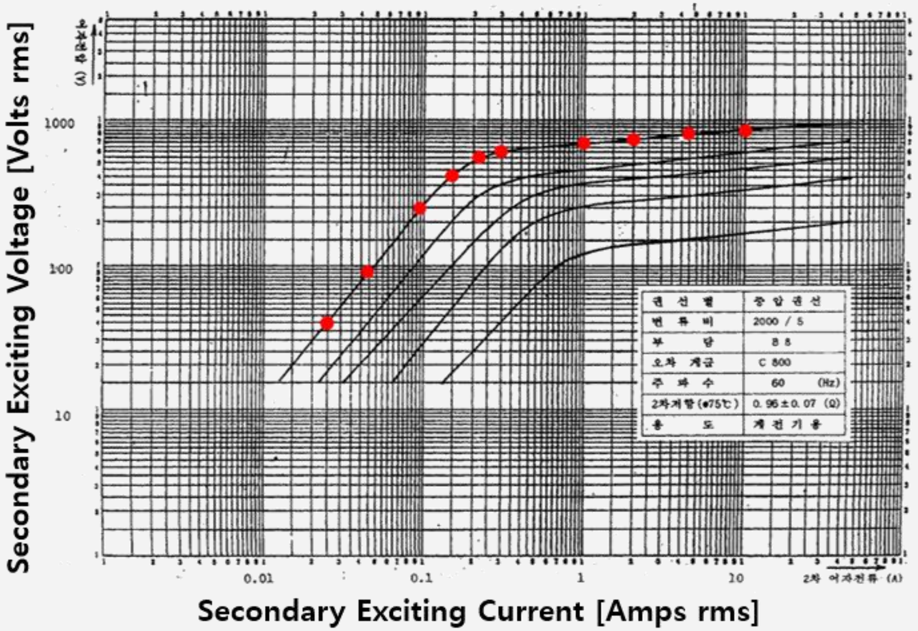
- **Proposed CT UDM(User Define Model) based on the modelling method of a nonlinear element suggested by Dommel**
  - Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve
    - ✓ L. A. N. Neves, H. W. Dommel, "On Modelling Iron Core Nonlinearities", IEEE Transactions on Power Systems, Volume 8, pp. 417 – 425, May 1993.
  - Network solution technique considering nonlinear circuit
    - ✓ H. W. Dommel, "Nonlinear and time-varying elements in digital simulation of electromagnetic transients", IEEE Trans. Power App. Syst., vol. PAS-90, pp. 2561-2567, Nov./Dec. 1971.

- **Simulation Studies**
  - Verification of the CT UDM and RTDS CT model by applying open circuit test
  - Apply UDM to the power system model in RSCAD

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

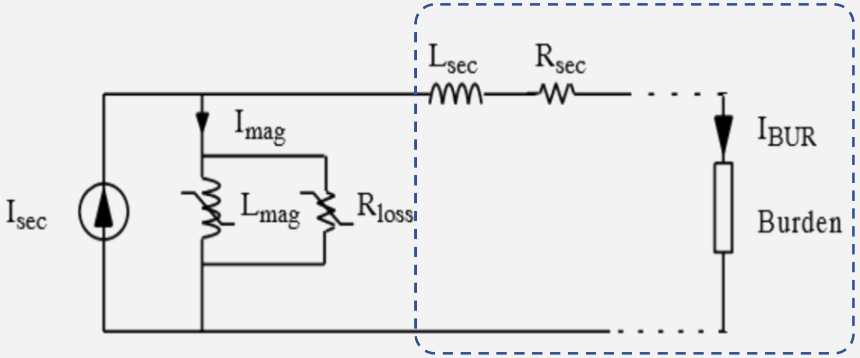
## Purpose & Target CT Equivalent Circuit

- ❖ $V_{rms} - I_{rms}$ based Excitation Curve (10 points data used)
  - Linear approximation of each segment

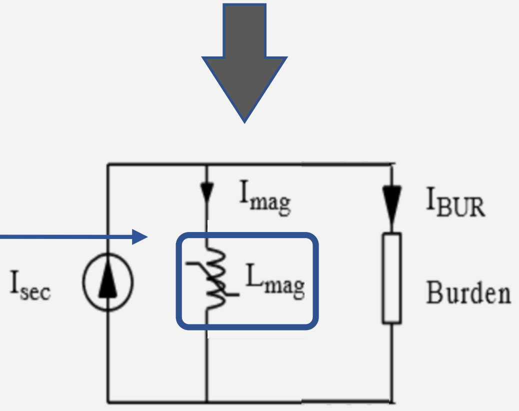



| | [ Irms ] | [ Vrms ] |
|---|---|---|
| Point 1 | 0.0129 | 40 |
| Point 2 | 0.0291 | 90 |
| Point 3 | 0.0816 | 250 |
| Point 4 | 0.134 | 400 |
| Point 5 | 0.209 | 550 |
| Point 6 | 0.283 | 600 |
| Point 7 | 0.984 | 700 |
| Point 8 | 1.98 | 750 |
| Point 9 | 4.48 | 800 |
| Point 10 | 9.98 | 850 |

C800 (2000:5) CT Excitation Curve




General CT Equivalent Circuit



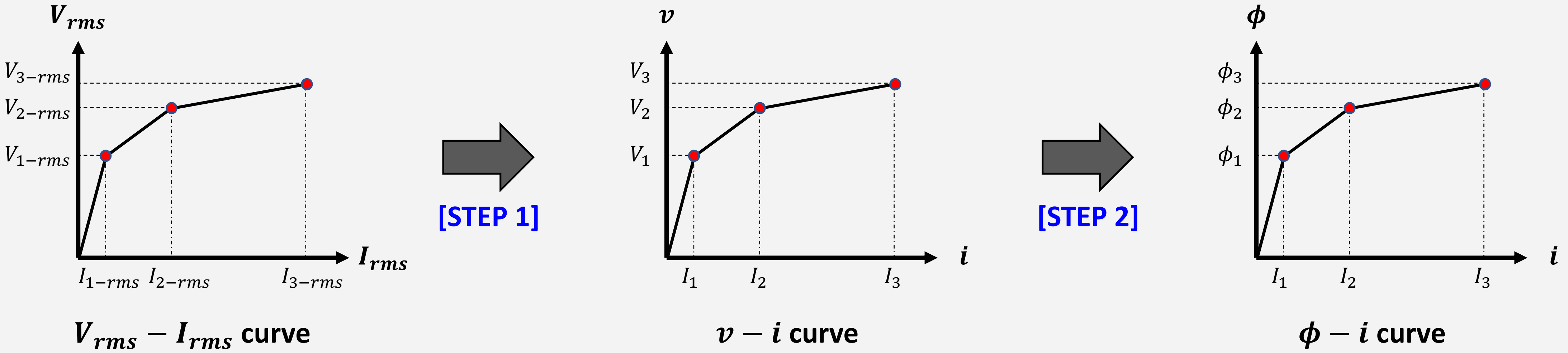

Proposed CT Equivalent Circuit

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

❖ **Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve**

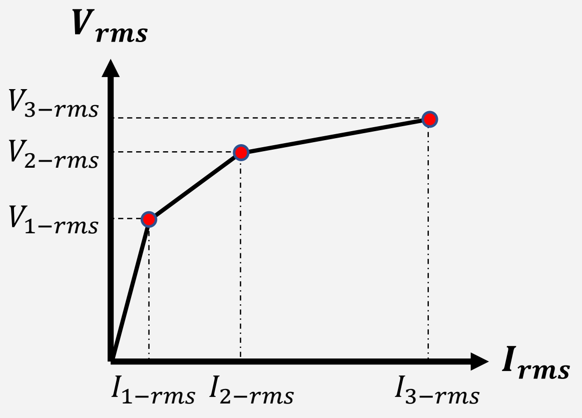
- ***10 points data** is used for modelling* nonlinear branch(magnetizing inductance) in UDM
- An example of the computation method using 3 points is below



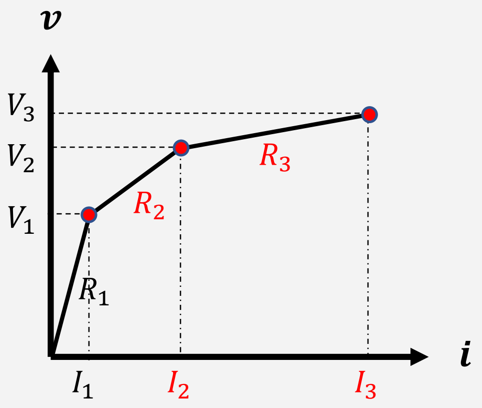
# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

❖ **Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve [STEP 1]**




**$V_{rms} - I_{rms}$ curve**




**$v - i$ curve**

**Obtaining the points $V_1, V_2, \ldots, V_k$ on the vertical axis is simply a re-scailing procedure form rms to peak values**

$$V_k = \sqrt{2} V_{k-rms}$$

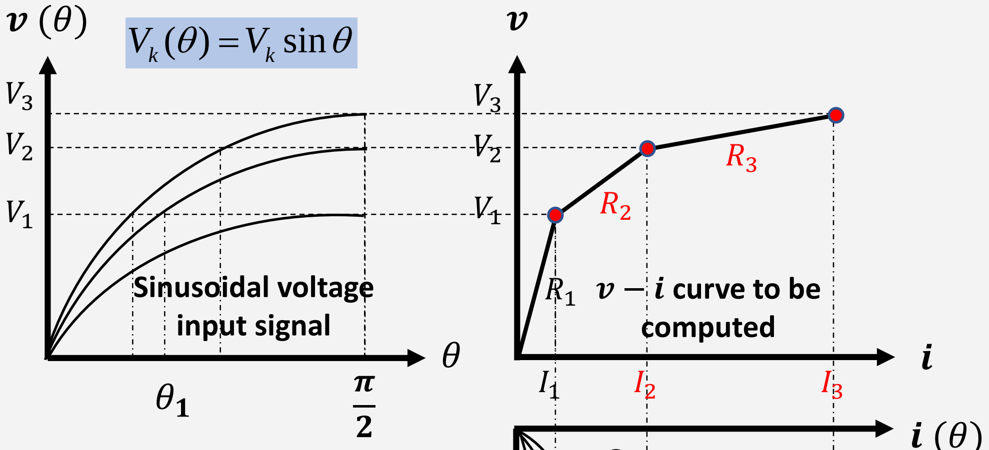
**Calculation of the peak current $I_1$ on the horizontal axis is straightforward (Since first point of Vrms, Irms is in the linear segment)**

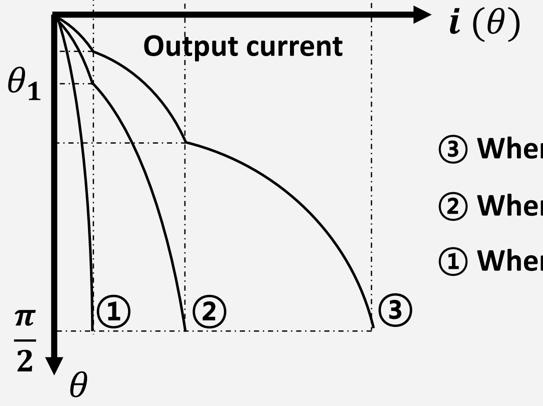
$$I_1 = \sqrt{2} I_{1-rms}$$

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

❖ **Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve [STEP 1]**




**Break points $\theta_1, \theta_2, \ldots \theta_{k-1}$**

$$\theta_j = \arcsin\left(\frac{V_j}{V_k}\right) \quad \text{for j=1,2,...,k-1}$$

③ **When, $V_k(\theta) = V_3 sin(\theta)$**

② **When, $V_k(\theta) = V_2 sin(\theta)$**

① **When, $V_k(\theta) = V_1 sin(\theta)$**

**Peak currnet $I_k$ is found from the definition of the rms value ($k \geq 2$)**

$$I^2_{rms} = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} i^2(\theta)\ d\theta$$

$$I^2_{k-rms} = \frac{2}{\pi}\Big[\int_0^{\frac{\pi}{2}} \Big(\frac{V_k \sin\theta}{R_1}\Big)^2 d\theta + \int_{\theta_1}^{\theta_2} \Big(I_1 + \frac{V_k \sin\theta - V_1}{R_2}\Big)^2 d\theta + \ldots + \int_{\theta_{k-1}}^{\frac{\pi}{2}} \Big(I_{k-1} + \frac{V_k \sin\theta - V_{k-1}}{R_k}\Big)^2 d\theta\Big]$$

**Unknown value** → $R_k$

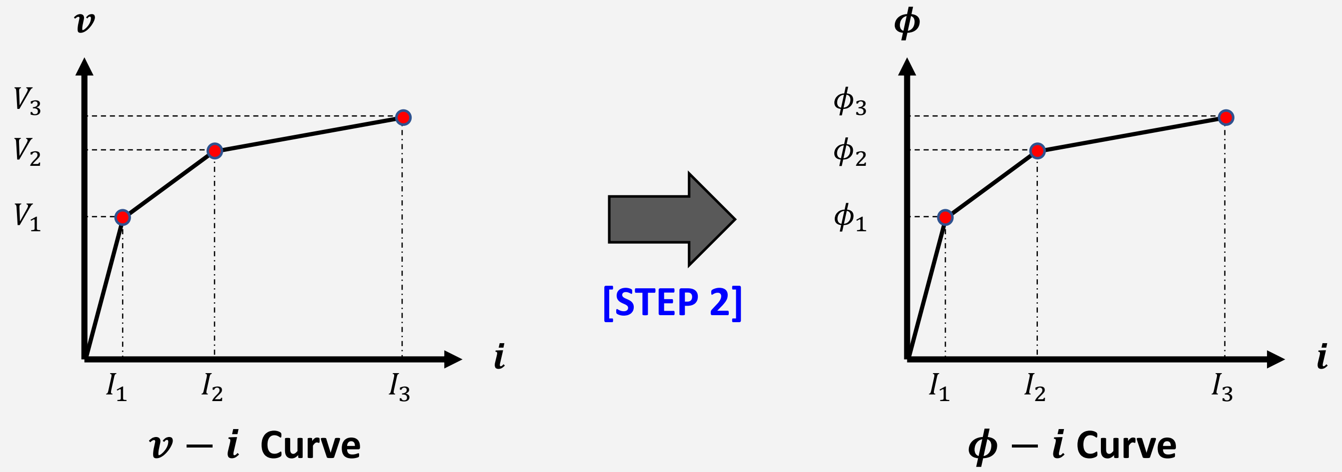
**Compute peak current $I_k$ using $R_k$**

$$I_k = \frac{V_k - V_{k-1}}{R_k} + I_{k-1}$$

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

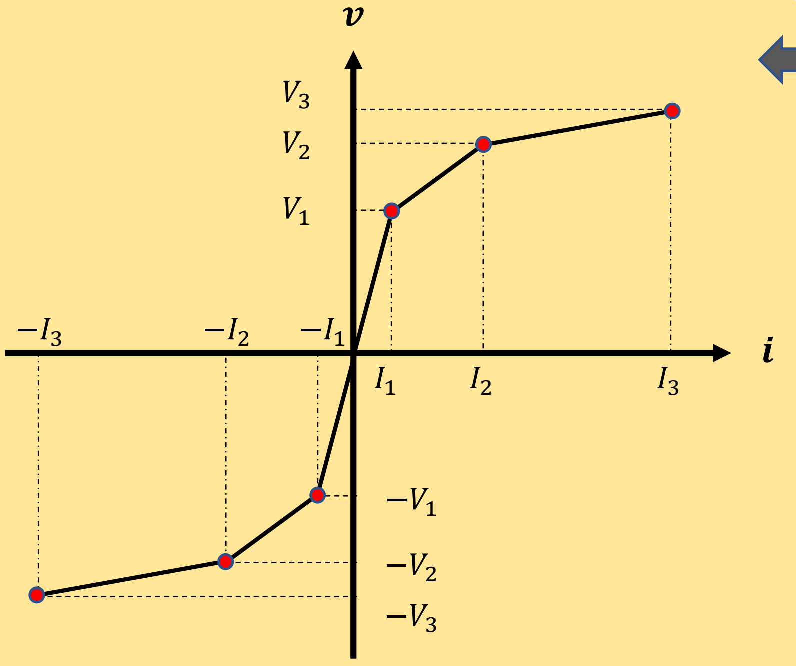
❖ **Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve [STEP 2]**



# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

❖ **Computation of the $\phi - i$ curve from the $V_{rms} - I_{rms}$ curve [STEP 2]**




**$v - i$ Curve**
**[Nonlinear Resistance]**

**Nonlinear resistance**

$$v(t) = f(\ i(t)\ )$$

**Nonlinear inductance**

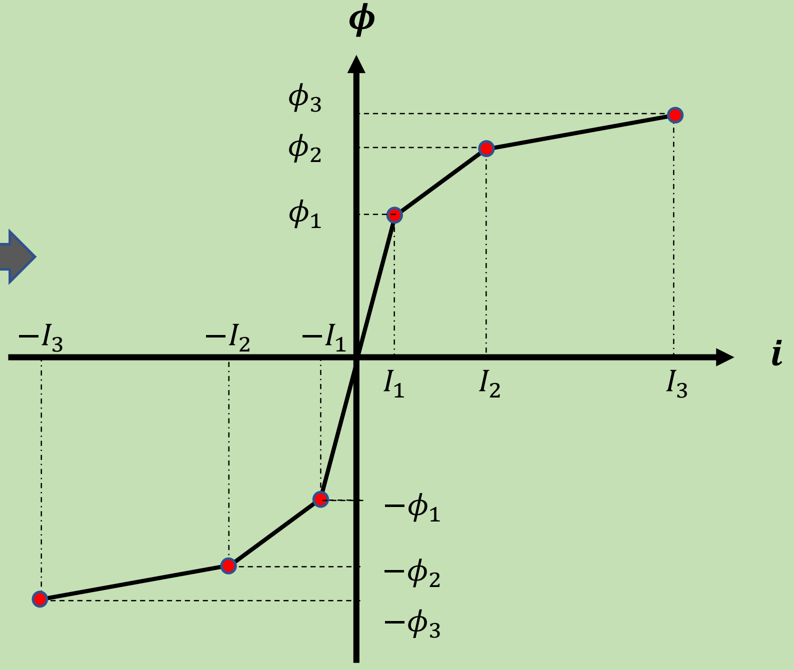
$$\phi(t) = f(\ i(t)\ )$$

$$\phi(t) = \int_{t-\Delta t}^{t} v(t)dt + \phi(t-\Delta t)$$

$$v(t) = \frac{2}{\Delta t}\phi(t) - v(t-\Delta t) - \frac{2}{\Delta t}\phi(t-\Delta t)$$

$$v(t) = \frac{2}{\Delta t}\phi(t) + B(t-\Delta t)$$

$$v(t) = \frac{2}{\Delta t} f(\ i(t)\ ) + B(t-\Delta t)$$

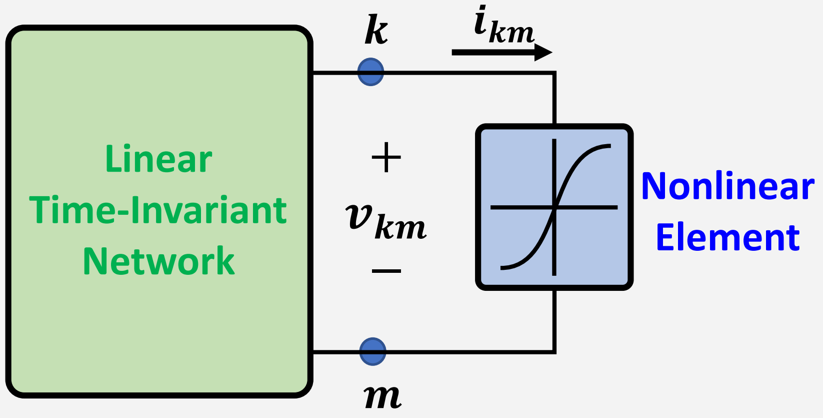



**$\phi - i$ Curve**
**[Nonlinear Inductance]**

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

- **Network solution technique condisering nonlinear circuit**
  - Compensation method can be applied if there is only one nonlinear element in the circuit
  - Nonlinear element is replaced by a current source $i_{km}$




**Linear network including only one nonlinear element**

Total network solution(final voltage)

$$v_{km}(t) = v_{km}^{linear}(t) - R_{Th} i_{km}(t)$$

Open circuit voltage of network
(without nonlinear element)

Thevenin resistance

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

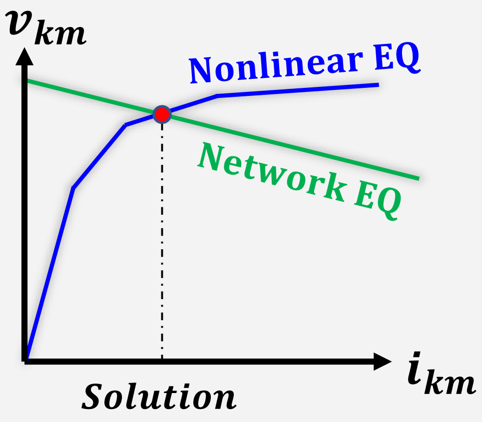
❖ **Network solution technique considering nonlinear circuit**

**The solution process in each time step**

① Compute node voltage without nonlinear element

② Solve the two scalar equations Network Equation and Nonlinear Equation simultaneously for $i_{km}$

③ Find the final voltage solution by super-imposing the response to the current source $i_{km}$




**Simultaneous solution of two equations**

**Network Equation** → $v_{km}(t) = v_{km}^{linear}(t) - R_{Th} i_{km}(t)$

**Nonlinear Equation** → $v_{km}(t) = \frac{2}{\Delta t} f\left(i_{km}(t)\right) + B(t - \Delta t)$

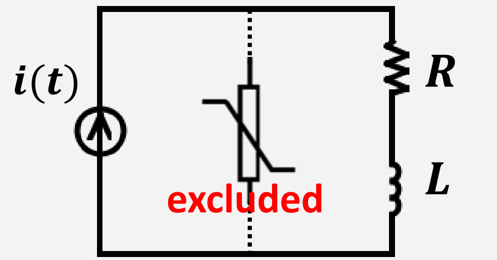
# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

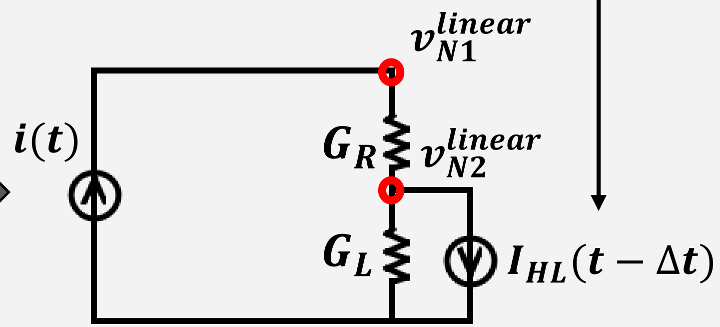
❖ **Network solution technique considering nonlinear circuit**

**The solution process in each time step**

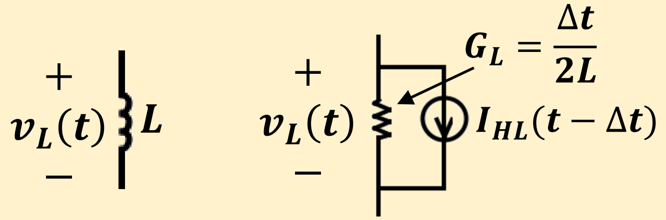
① Compute node voltage without nonlinear element




**Proposed CT Equivalent Circuit without nonlinear element**




**Dommel Equivalent Circuit**




$$i_L(t) = \frac{\Delta t}{2L} v_L(t) + I_{HL}(t-\Delta t)$$

Norton equivalent of inductor

$$\begin{bmatrix} v_{N1}^{linear}(t) \\ v_{N2}^{linear}(t) \end{bmatrix} = \begin{bmatrix} G_R & -G_R \\ -G_R & G_R + G_L \end{bmatrix}^{-1} \begin{bmatrix} i(t) \\ -I_{HL}(t-\Delta t) \end{bmatrix}$$

**Vector of nodal voltages** | **Conductance matrix** | **Vector of external current sources**

Nodal equation

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

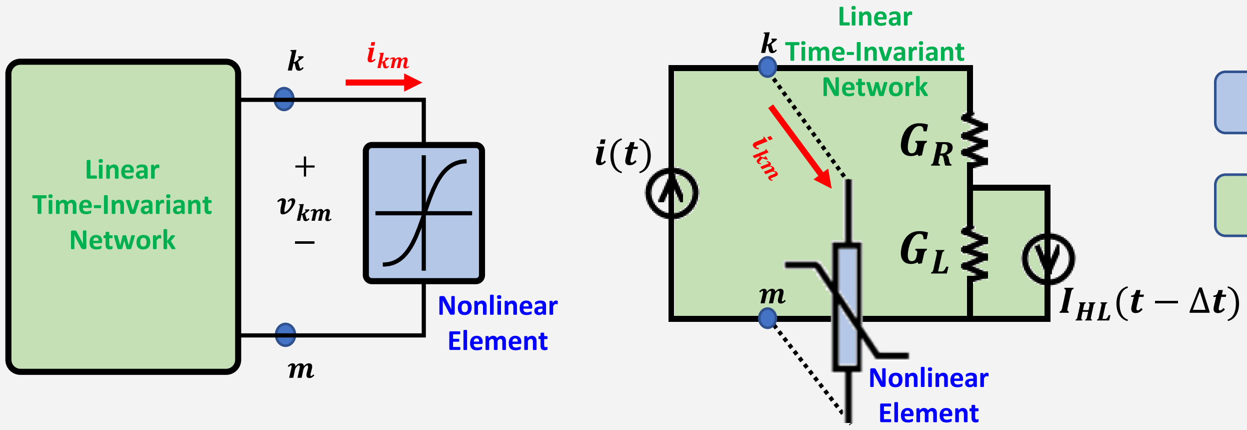
## Proposed CT UDM

❖ **Network solution technique considering nonlinear circuit**

**The solution process in each time step**

② Solve the two scalar equations Network Equation and Nonlinear Equation simultaneously for $i_{km}$

③ Find the final voltage solution by super-imposing the response to the current source $i_{km}$




**Linear network including only one nonlinear element**

**Nonlinear Equation** → $v_{km}(t) = \frac{2}{\Delta t} f\left(i_{km}(t)\right) + B(t-\Delta t)$

**Network Equation** → $v_{km}(t) = v_{km}^{linear}(t) - R_{Th} i_{km}(t)$

**Final voltage** ($v_{km}(t)$)

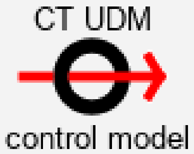
**Open circuit voltage of network** ($v_{km}^{linear}(t)$)

**Thevenin resistance** ($R_{Th}$)

# DEVELOPMENT OF A CT UDM(USER DEFINE MODEL)

## Proposed CT UDM

❖ **CT UDM & model parameters**




**Current_Transformer.def**

BURDEN | Vrms Irms DATA | SIGNAL NAMES
MAIN DATA | PROCESSOR ASSIGNMENT | TRANSFORMER DATA

| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| Vrms1 | | 40.0 | | 0.0 | |
| Irms1 | | 0.0 | | 0.0 | |
| Vrms2 | | 90.0 | | 0.0 | |
| Irms2 | | 0.0 | | 0.0 | |
| Vrms3 | | 250.0 | | 0.0 | |
| Irms3 | | 0.0 | | 0.0 | |
| Vrms4 | | 400.0 | | 0.0 | |
| Irms4 | | 0.0 | | 0.0 | |
| Vrms5 | | 550.0 | | 0.0 | |
| Irms5 | | 0.0 | | 0.0 | |
| Vrms6 | | 600.0 | | 0.0 | |

Update | Cancel | Cancel All

**Current_Transformer.def**

BURDEN | Vrms Irms DATA | SIGNAL NAMES
MAIN DATA | PROCESSOR ASSIGNMENT | TRANSFORMER DATA

| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| Rbi | Burden series resistance | 1 | Ohms | 1e-9 | |
| Lbi | Burden series inductance | 1e-9 | H | 1e-9 | |

**Current_Transformer.def**

BURDEN | Vrms Irms DATA | SIGNAL NAMES
MAIN DATA | PROCESSOR ASSIGNMENT | TRANSFORMER DATA

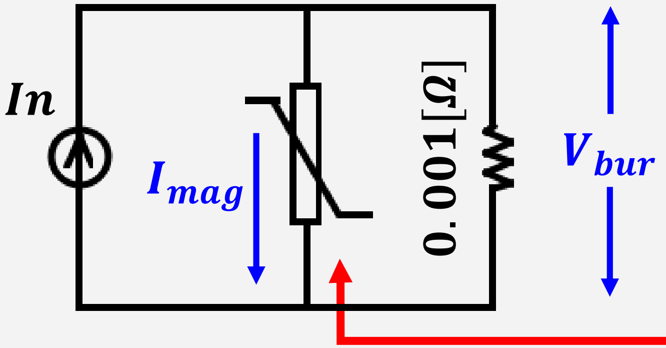
| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| Isec | Total Secondary Current Name | Isec_UDM | | | |
| Ibur | Burden Current Name | Ibur_UDM | | | |
| Imag | Magnetizing Current Name | Imag_UDM | | | |
| Flux | Flux Name | Flux_UDM | | | |
| Vbur | Burden Voltage Name | Vbur_UDM | | | |

# SIMULATION STUDIES

## Verification of the CT UDM by applying open circuit test

❖ **Simulation Conditions**

- Compared Models
  - ✓ CT UDM
  - ✓ RTDS CT model
- Input Signal
  - ✓ Sinusoidal current




**Proposed CT Equivalent Circuit**

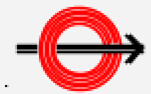
| | [ Irms ] | [ Vrms ] |
|---|---|---|
| Point 1 | 0.0129 | 40 |
| Point 2 | 0.0291 | 90 |
| Point 3 | 0.0816 | 250 |
| Point 4 | 0.134 | 400 |
| Point 5 | 0.209 | 550 |
| Point 6 | 0.283 | 600 |
| Point 7 | 0.984 | 700 |
| Point 8 | 1.98 | 750 |
| Point 9 | 4.48 | 800 |
| Point 10 | 9.98 | 850 |

# SIMULATION STUDIES

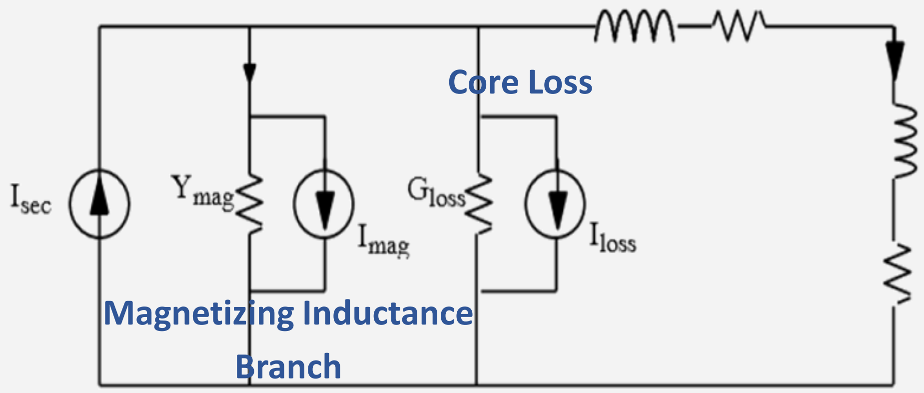
## Verification of the CT UDM by applying open circuit test

### ① Using RTDS CT Model

- **Input Saturation Characteristics Data Types**
  1) Physical Core Data
  2) B-H Characteristic Data
  3) Vrms-Irms Characteristic Data



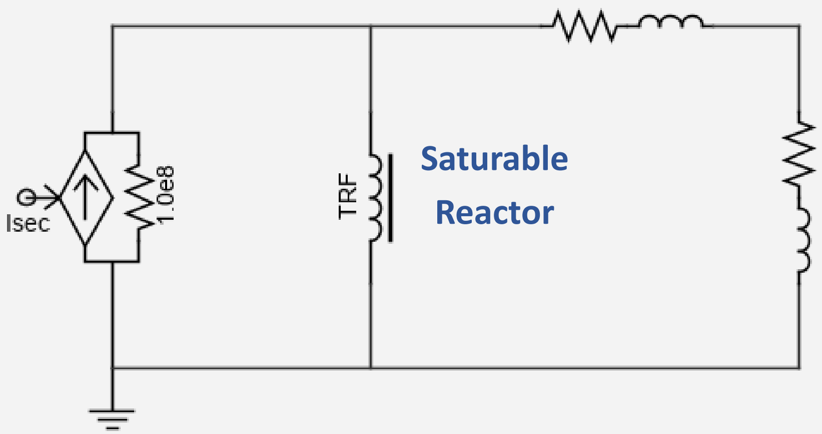
RTDS CT Model




RTDS CT Equivalent Circuit

### ② ~~Using RTDS Saturable Reactor Model~~

- **Construct a CT equivalent circuit using Saturable Reactor Model**
- **Input Saturation Characteristics Data**
  - ✓ Linear Inductance, Knee-point Voltage, Air Core Inductance

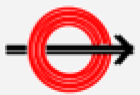



CT Equivalent Circuit using RTDS Saturable Reactor

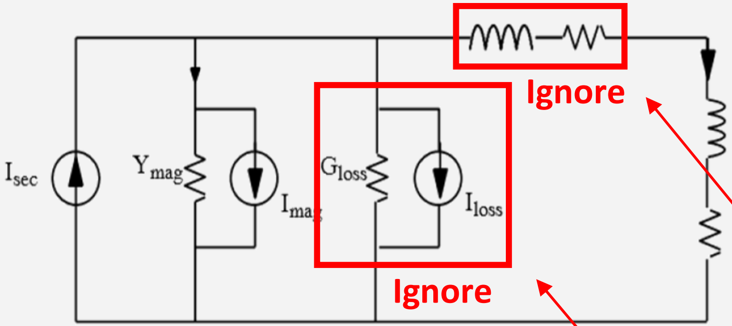
# SIMULATION STUDIES

## Verification of the CT UDM by applying open circuit test

❖ **Ignore Core Loss, Secondary Resistance and Leakage Reactance**



RTDS CT Model




RTDS CT Equivalent Circuit

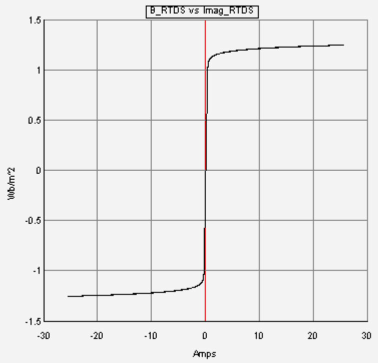
| V1,I1 ... V10,I10 | P-LOSS DATA | MONITORING | SIGNAL NAMES |
|---|---|---|---|
| MAIN DATA | PROCESSOR ASSIGNMENT | TRANSFORMER DATA | BURDEN |

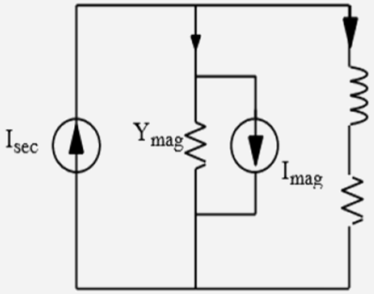
| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| Rs | Secondary Side Resistance | 0.0 | Ohms | 0.0 | |
| Ls | Secondary Side Inductance | 0.0 | H | 0.0 | |
| Ratio | Turns ratio | 1 | | 0 | |

| V1,I1 ... V10,I10 | P-LOSS DATA | MONITORING | SIGNAL NAMES |
|---|---|---|---|
| MAIN DATA | PROCESSOR ASSIGNMENT | TRANSFORMER DATA | BURDEN |

| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| LoopW | Loop Width | 0 | % | 0 | 100 |

RTDS CT Parameters Menu



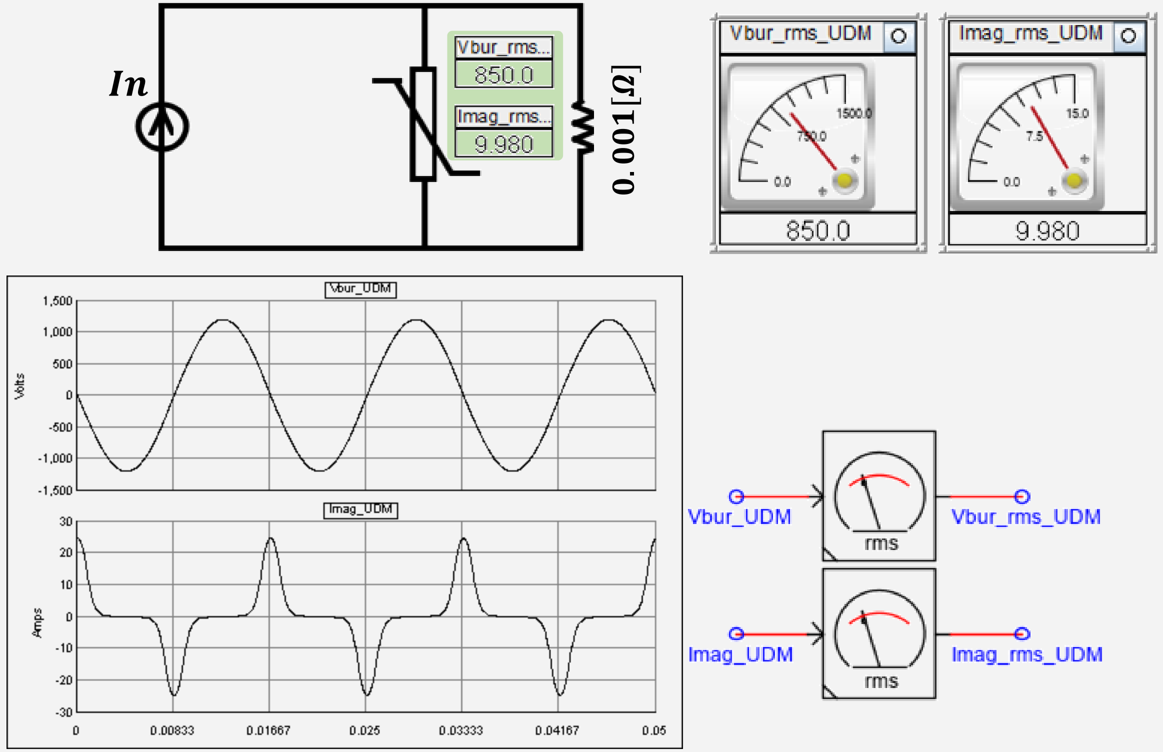

Proposed CT Equivalent Circuit

# SIMULATION STUDIES

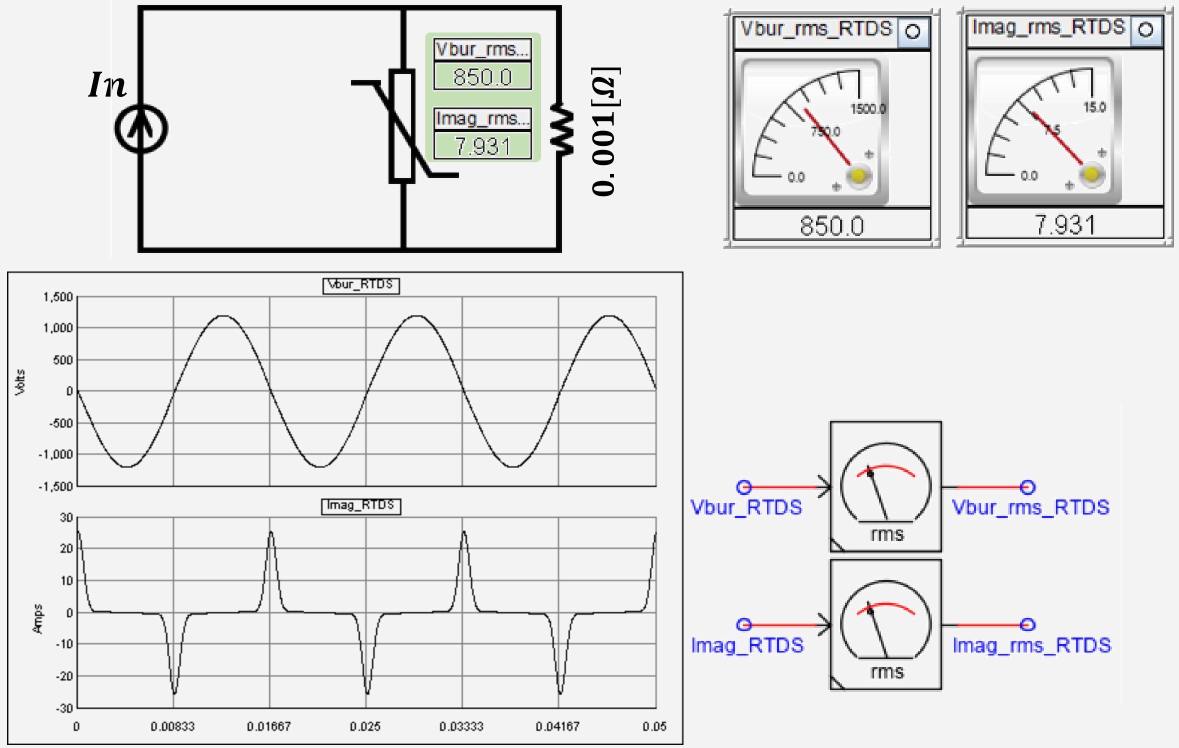
## Verification of the CT UDM by applying open circuit test

❖ **Burden voltage of 850 [rms volts]**

**CT UDM**




**RTDS CT**

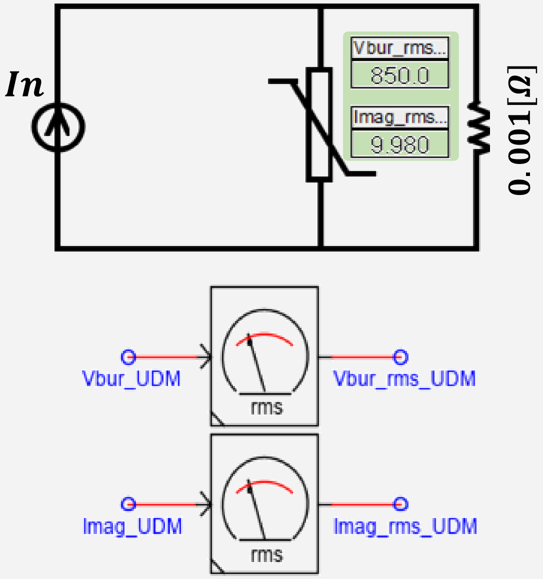


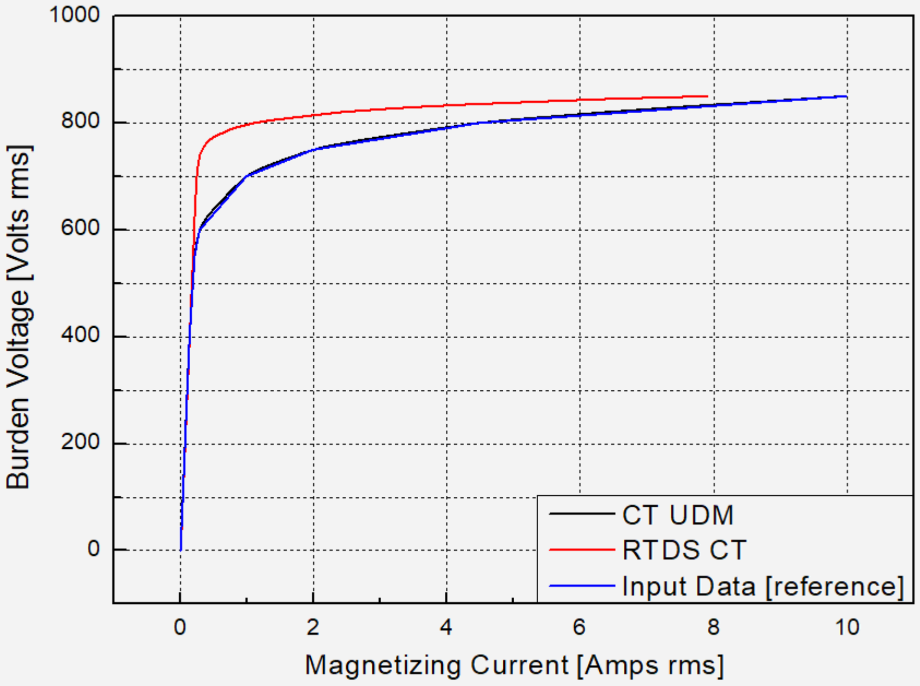
# SIMULATION STUDIES

## Verification of the CT UDM by applying open circuit test

❖ **Change burden voltage from 0 to 850 [rms volts] by using script**

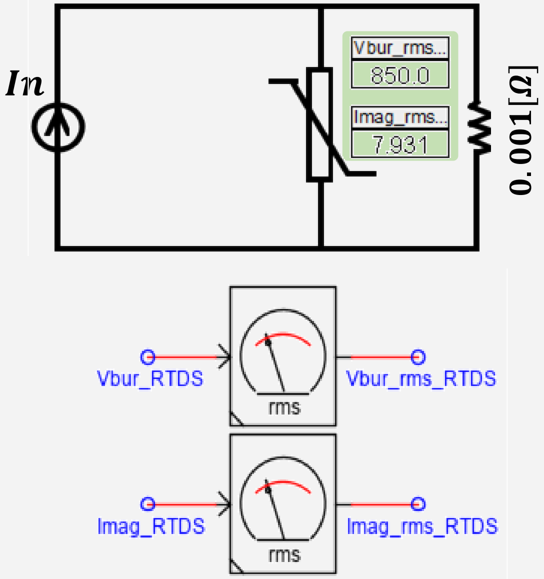
CT UDM




**Test results**

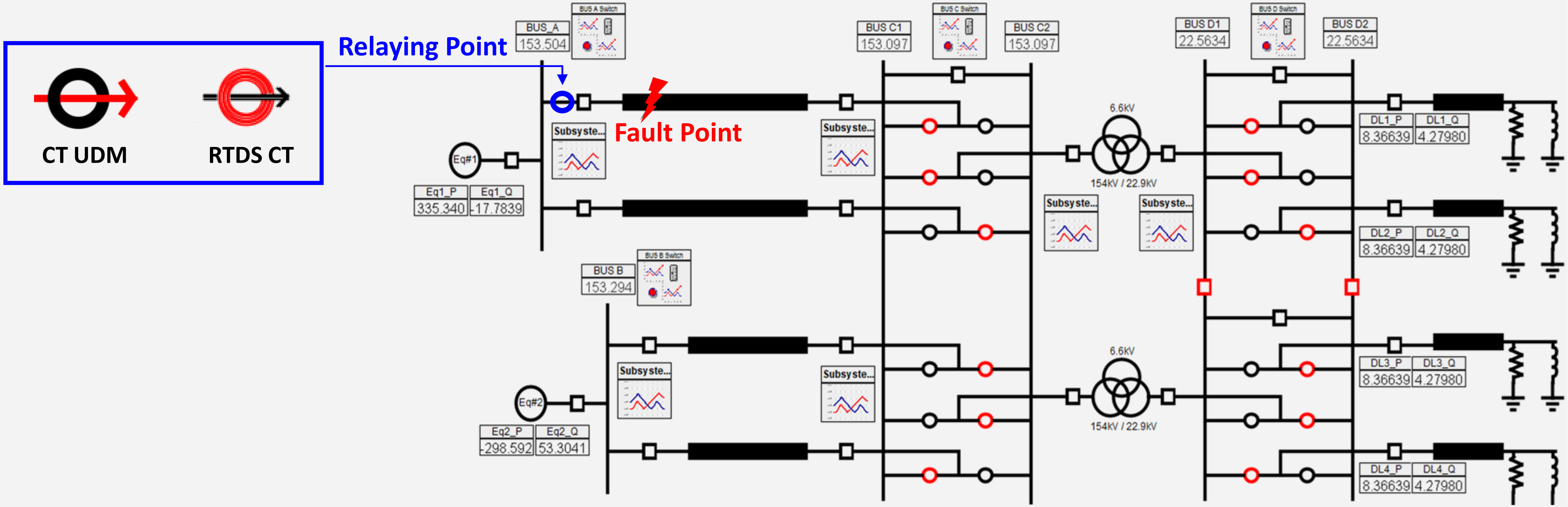
RTDS CT



# SIMULATION STUDIES

## Apply CT UDM to the power system

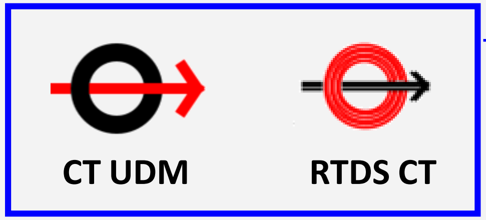
❖ **154 - 22.9kV Power system**

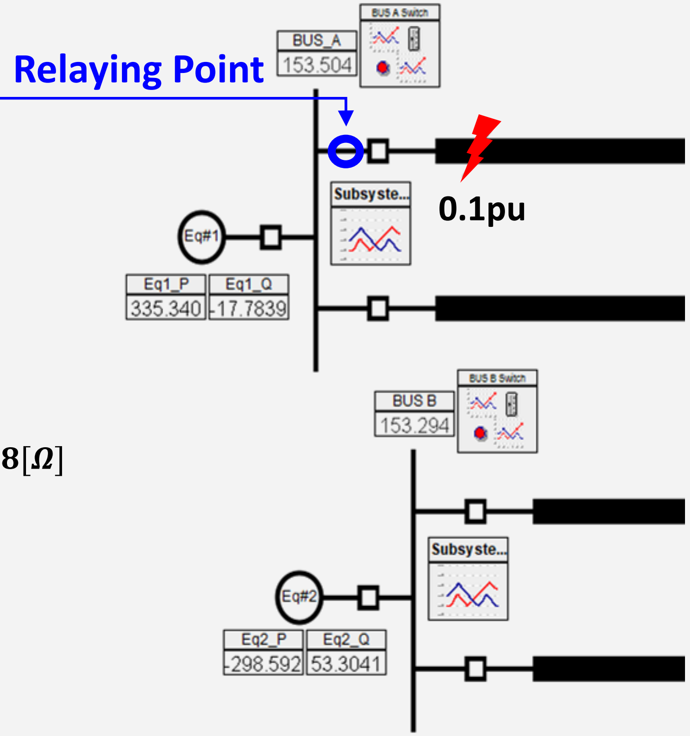


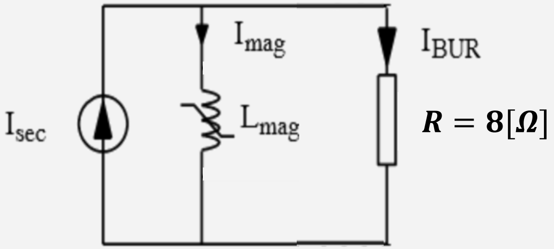
# SIMULATION STUDIES

## Apply CT UDM to the power system

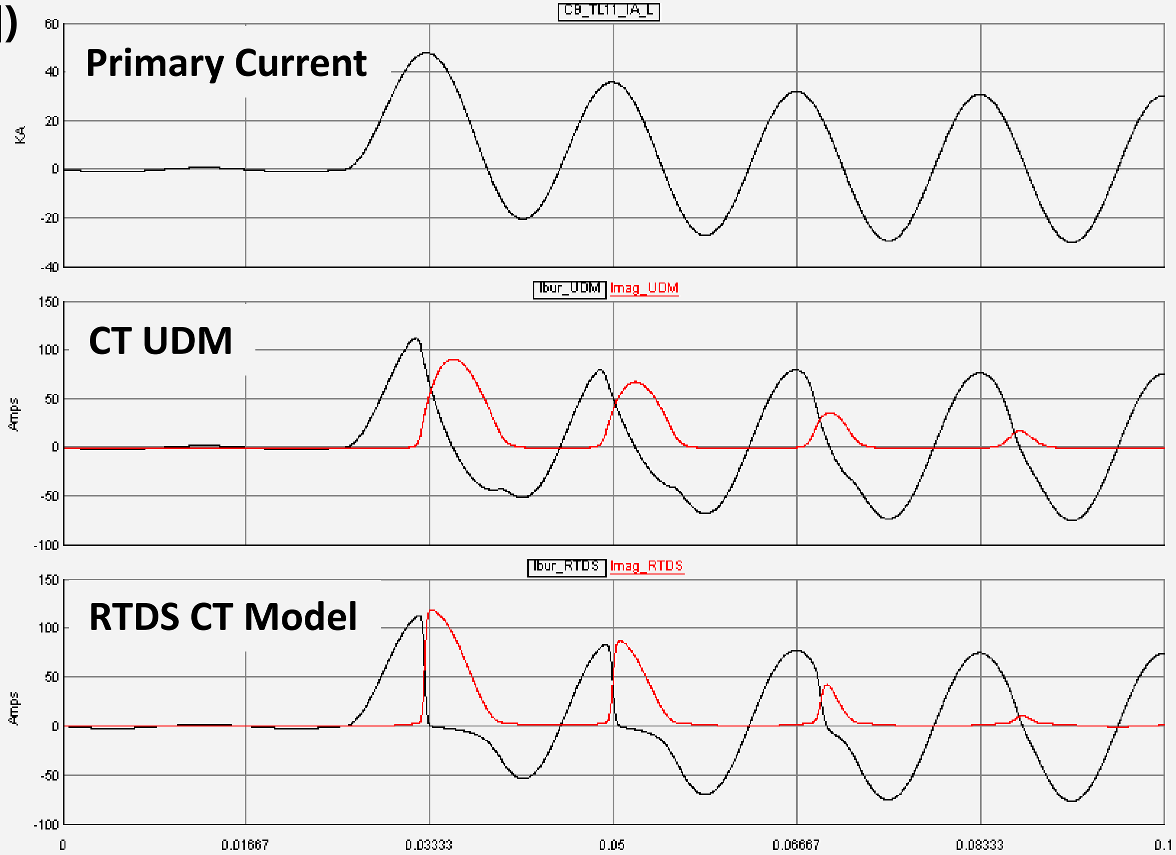
- **Single Line to Ground Fault (Fault Angle : 0[deg])**
- **CT Load 8[Ω] (R = 8[Ω] pf 1.0)**



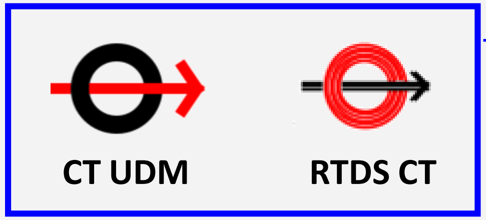

**Proposed CT Equivalent Circuit**

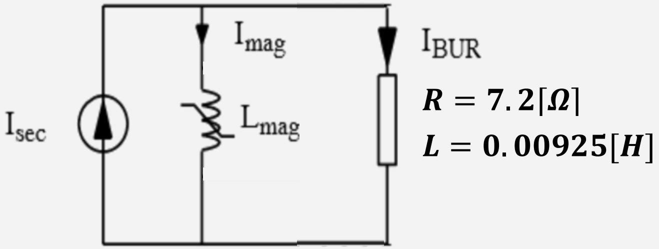


# SIMULATION STUDIES

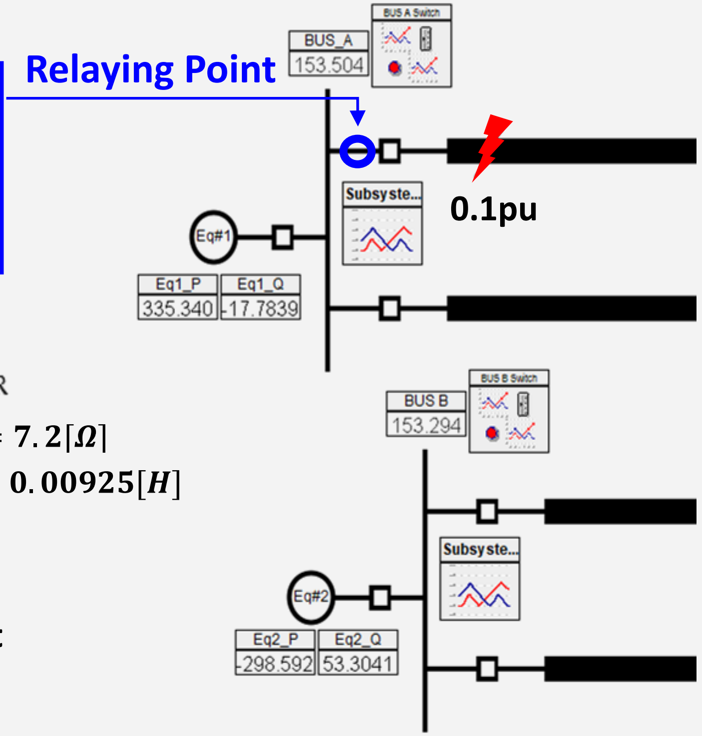
## Apply CT UDM to the power system

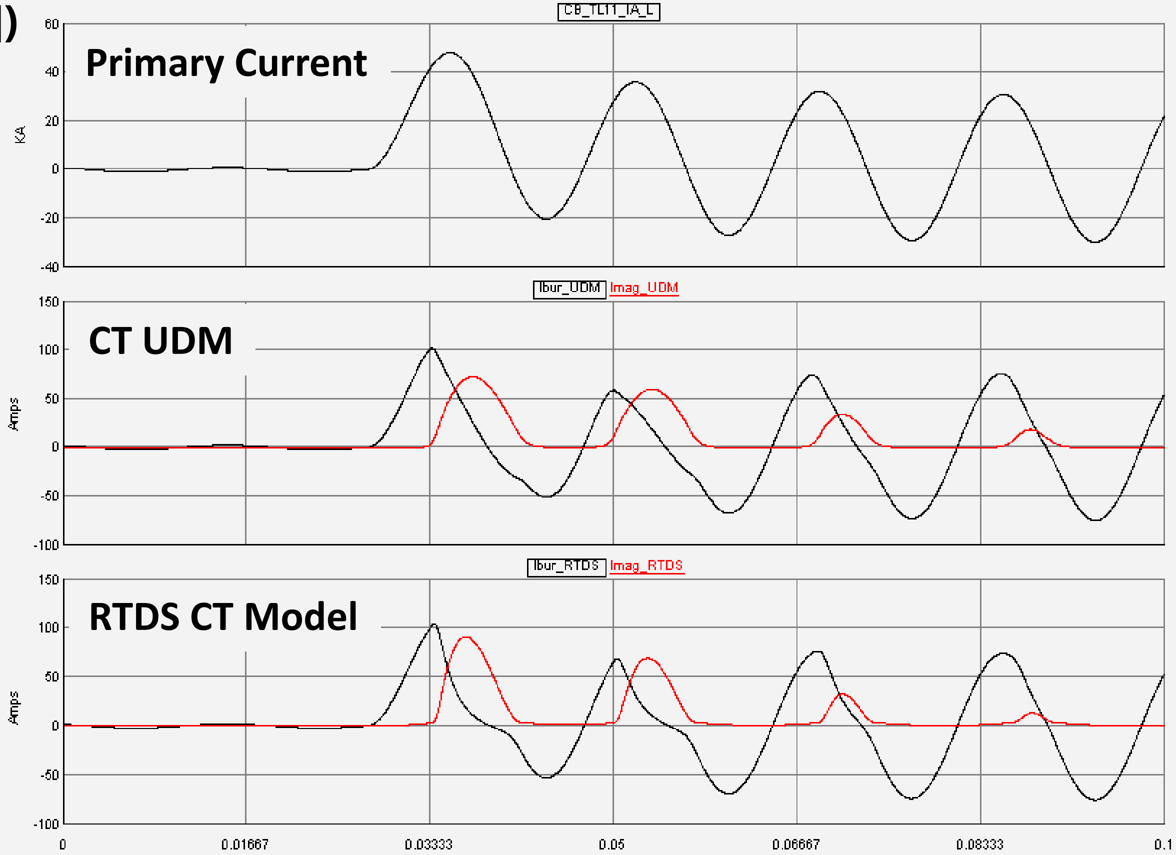
- **Single Line to Ground Fault (Fault Angle : 0[deg])**
- **CT Burden 8[Ω] (R = 7.2[Ω], L = 0.00925[H] pf 0.9)**




**Proposed CT Equivalent Circuit**



# CONCLUSIONS

- Summary of the presentation
  - When Vrms-Irms data is applied to the RTDS CT model, the curve obtained from its simulation is a bit different from the applied Vrms-Irms data
  - CT UDM which accurately reflects input data was developed using computation method of the peak data from rms data and network solution technique(nonlinear element is included)
  - Verity the performance of the CT UDM by using open circuit test and apply to the power system

→ Can be regarded as an effective method to simulate the CT saturation phenomenon

- Future Studies
  - Consider Core Loss (Hysteresis loss & Eddy current loss)
  - Consider residual flux simulation

# REFERENCES


① L. A. N. Neves, H. W. Dommel, "On Modelling Iron Core Nonlinearities", IEEE Transactions on Power Systems, Volume 8, pp. 417 – 425, May 1993.

② H. W. Dommel, "Nonlinear and time-varying elements in digital simulation of electromagnetic transients", IEEE Trans. Power App. Syst., vol. PAS-90, pp. 2561-2567, Nov./Dec. 1971.

③ RTDS “POWER SYSTEM COMPONENTS MANUAL”

# THANK YOU FOR YOUR ATTENTION