IEEE ISGT2010, Jan. 21

Voltage Stability and Sensitivity Analysis Considering Dynamic Load for Smart Grid

S. Lian, S. Morii,
T. Ishii and S. Kawamoto
Osaka Prefecture University
Osaka, JAPAN

Contents

Ⅰ. Introduction

Electricity Deregulation

Load and Distributed Generators

Stable supply of electricity

Blackouts

1987 August: TOKYO

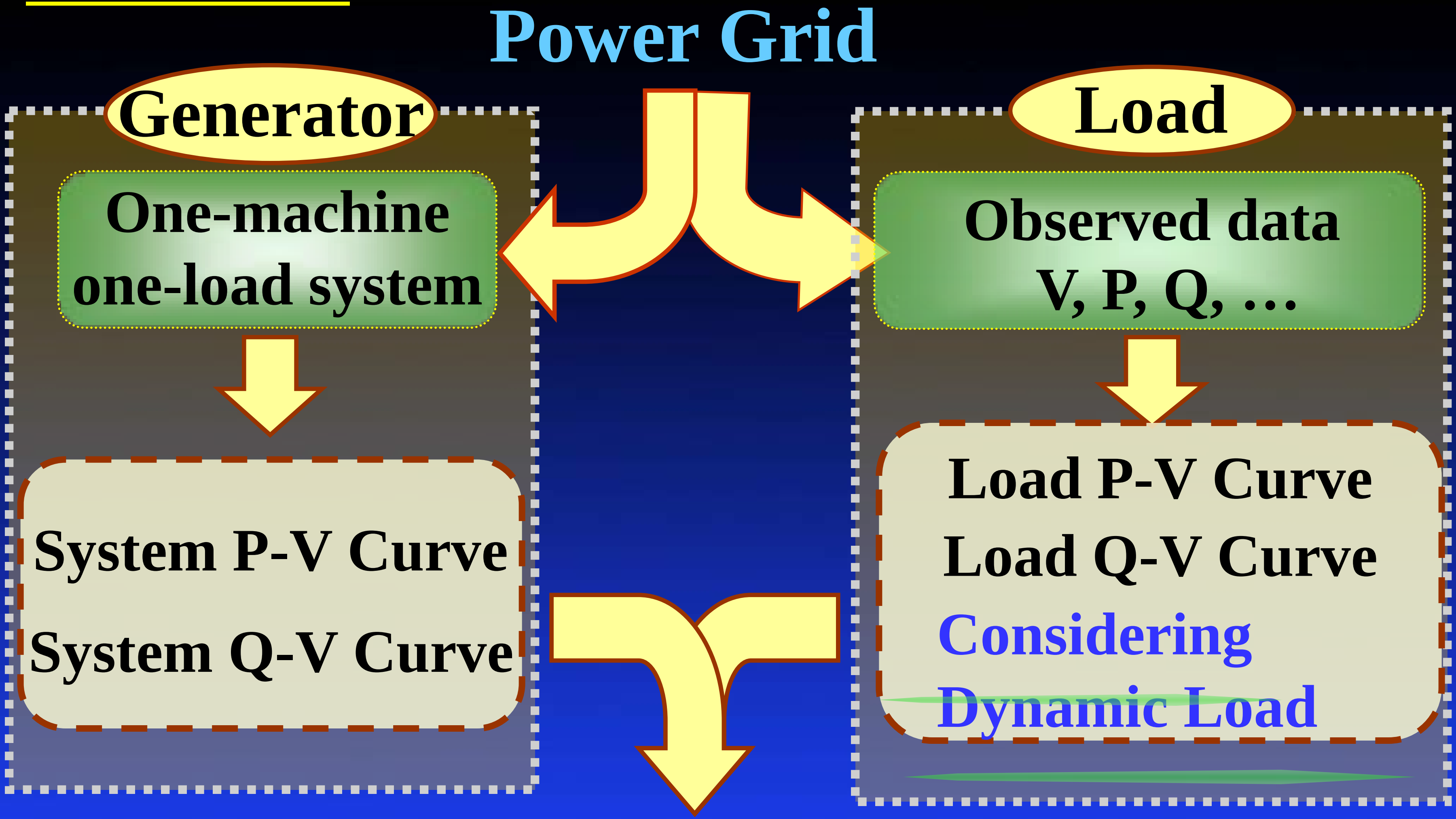
2003 August: United States, Canada

September: Sweden, Denmark, Italy

Increase of reactive power

Load Control based on Load Analysis

Research flow



Power Grid

Generator

One-machine one-load system

System P-V Curve

System Q-V Curve

Load

Observed data

V, P, Q, …

Load P-V Curve

Load Q-V Curve

Considering Dynamic Load

Load Composition and Voltage Stability Analysis

Ⅱ．Power Flow in Power Grid

Looking over the upper system at a certain load-bus

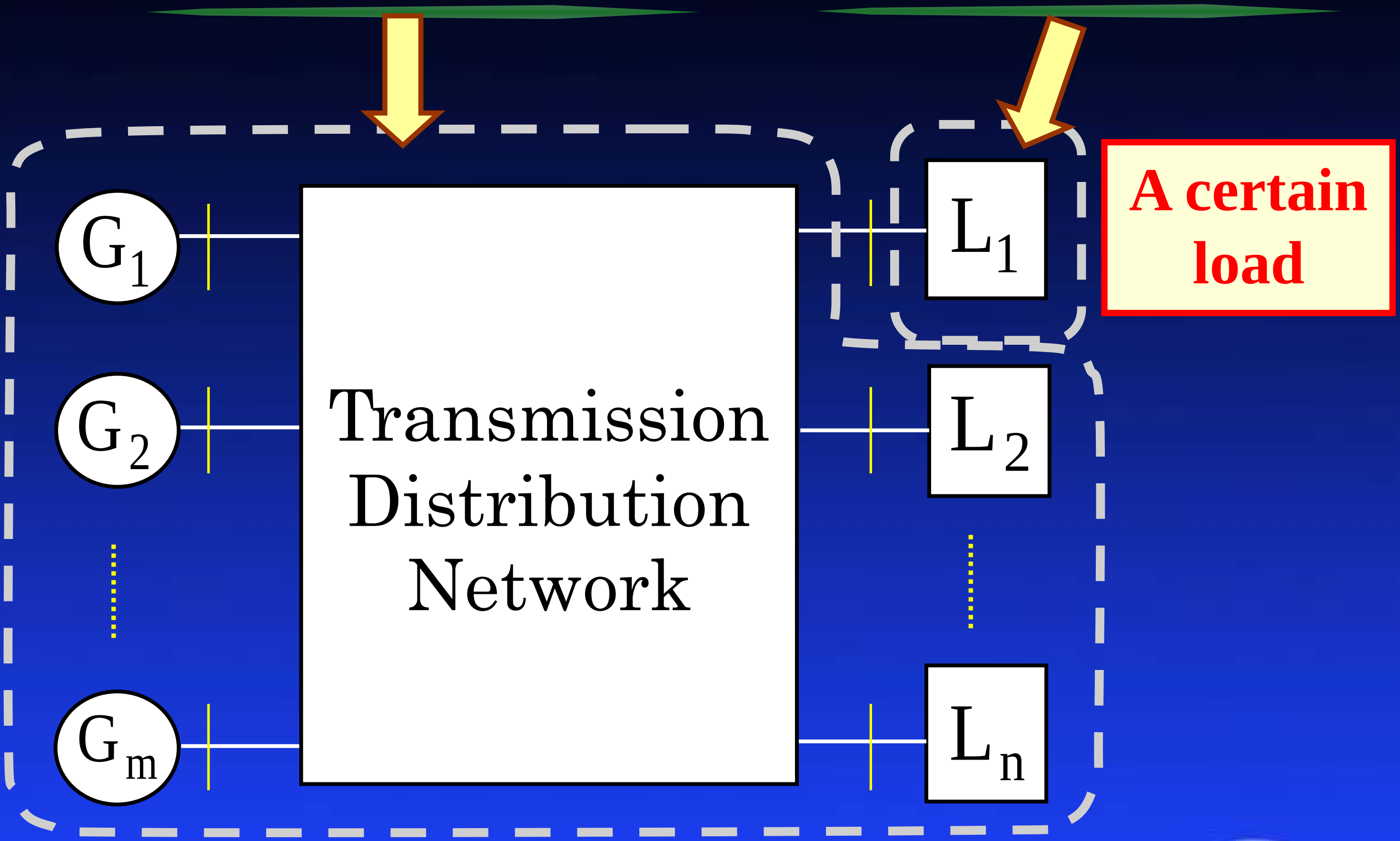


Fig. 1 Power grid

Power Flow ①

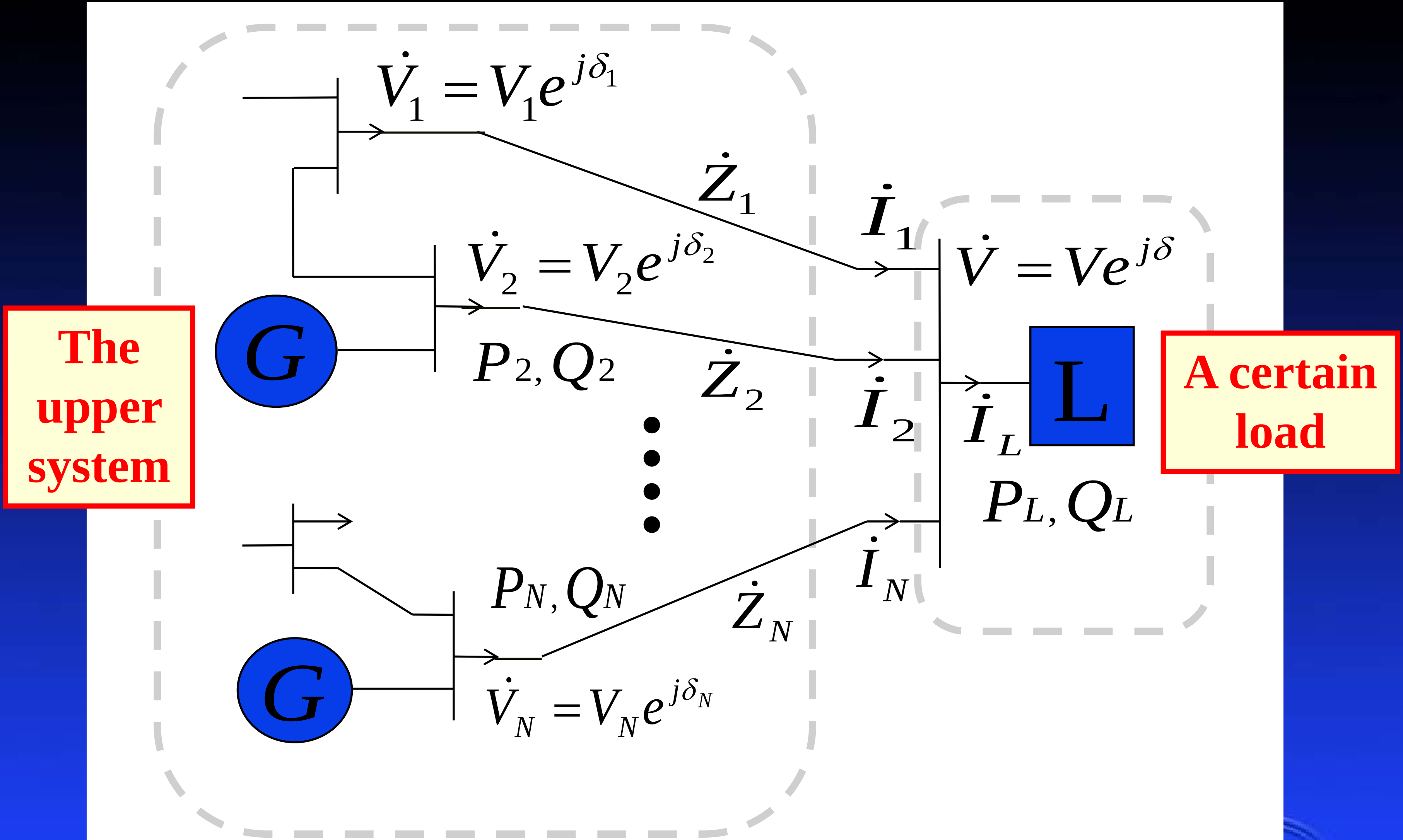


Fig. 2 Power flow at a load-bus

Power Flow ②

$$P_L + jQ_L = \dot{V}\overline{\dot{I}}_L \qquad \textbf{(1)}$$

$$= \dot{V}\overline{\left(\dot{I}_1 + \dot{I}_2 + \cdots + \dot{I}_N\right)}$$

$$= \dot{V}\overline{\left(\frac{\dot{V}_1 - \dot{V}}{\dot{Z}_1} + \frac{\dot{V}_2 - \dot{V}}{\dot{Z}_2} + \cdots + \frac{\dot{V}_N - \dot{V}}{\dot{Z}_N}\right)}$$

$$= \dot{V}\overline{\left\{\left(\frac{1}{\dot{Z}_1}\dot{V}_1 + \frac{1}{\dot{Z}_2}\dot{V}_2 + \ldots + \frac{1}{\dot{Z}_N}\dot{V}_N\right) - \left(\frac{1}{\dot{Z}_1} + \frac{1}{\dot{Z}_2} + \ldots + \frac{1}{\dot{Z}_N}\right)\dot{V}\right\}}$$

$$= \dot{V}\overline{\left\{\frac{\underbrace{\boxed{\left(\dfrac{\frac{1}{\dot{Z}_1}\dot{V}_1 + \frac{1}{\dot{Z}_2}\dot{V}_2 + \ldots + \frac{1}{\dot{Z}_N}\dot{V}_N}{\frac{1}{\dot{Z}_1} + \frac{1}{\dot{Z}_2} + \ldots + \frac{1}{\dot{Z}_N}}\right)}}_{\dot{V}_0} - \dot{V}}{\underbrace{\boxed{1 \Big/ \left(\frac{1}{\dot{Z}_1} + \frac{1}{\dot{Z}_2} + \ldots + \frac{1}{\dot{Z}_N}\right)}}_{\dot{Z}_0}}\right\}}$$

$$\equiv \dot{V}\overline{\left(\frac{\dot{V}_0 - \dot{V}}{\dot{Z}_0}\right)}$$

$$\dot{V}_0 \equiv \sum_{k=1}^{N}\left(\dot{V}_k \big/ \dot{Z}_k\right) \Big/ \sum_{k=1}^{N}\left(1 \big/ \dot{Z}_k\right) \qquad \textbf{(2)}$$

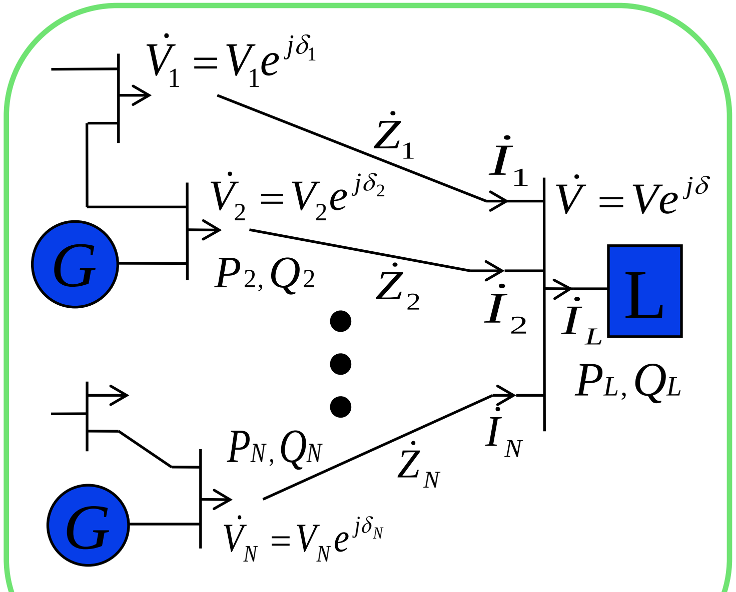


Fig.2 Power flow at a load-bus

Power Flow ③

$$P_L + jQ_L \equiv \dot{V}\overline{\left(\frac{\dot{V}_0 - \dot{V}}{\dot{Z}_0}\right)} \;, \quad \left\{\begin{array}{l} \dot{V}_0 \equiv \sum_{k=1}^{N}\left(\dot{V}_k / \dot{Z}_k\right) \Big/ \sum_{k=1}^{N}\left(1/\dot{Z}_k\right) \\ \dot{Z}_0 \equiv 1 \Big/ \sum_{k=1}^{N}\left(1/\dot{Z}_k\right) \end{array}\right. \qquad (2)$$

The upper system can be rewritten into a one-machine one-load system without approximation.

Complicated power source

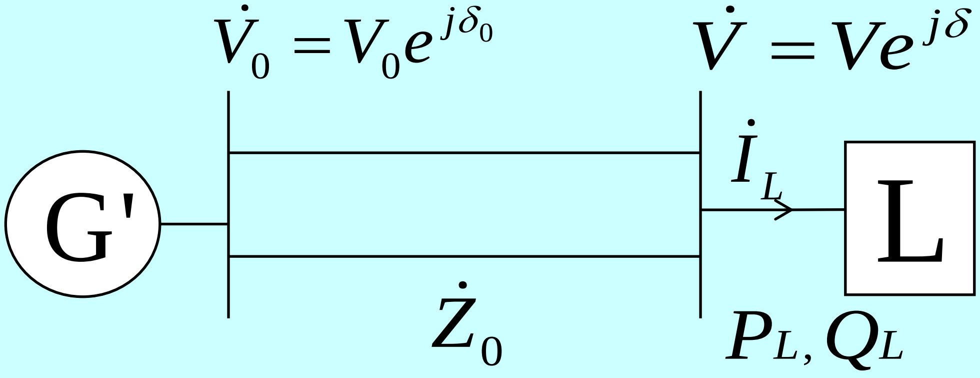


Fig. 3 Equivalent one-machine one-load system

Ⅲ．Load Modeling

Static Load Model

- **Exponential-type** $P = P_0 V^n$ **(3)**
  - ⋮
- **Polynomial-type** $P = \underbrace{\boxed{a_0}}_{\text{Constant power}} + \overbrace{\boxed{a_1 V}}^{\text{Constant current}} + \underbrace{\boxed{a_2 V^2}}_{\text{Constant impedance}}$ **(4)**
  - ⋮

⇩

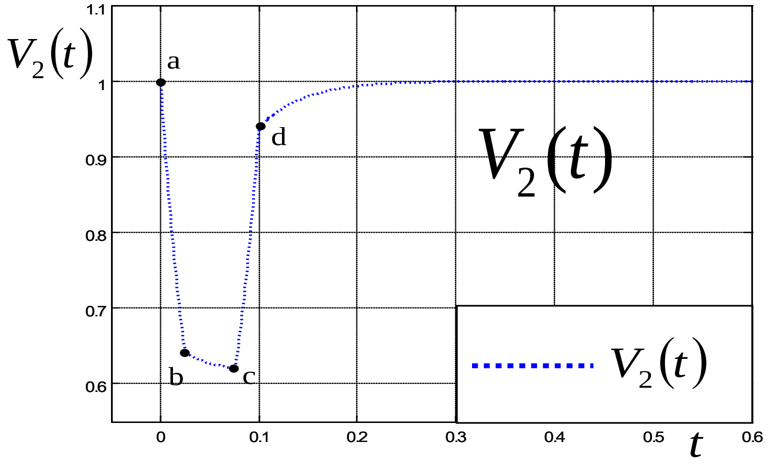
Dynamic Load Model

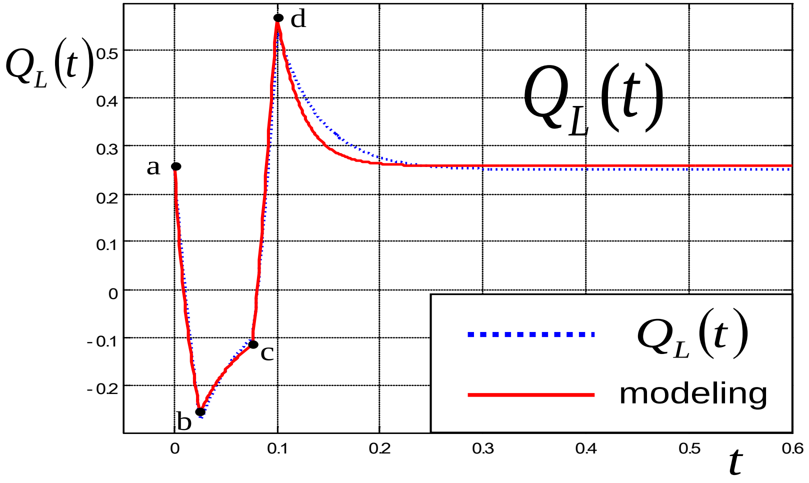
$$P_L(t) = \overbrace{\boxed{a_0 + a_1 V_2(t)}}^{\text{Static load}} + \overbrace{\boxed{a_2\left(\overset{\text{Conductance}}{G(t)} V_2^{\,2}(t) - 1\right)}}^{\text{Dynamic load}} \qquad (5)$$

$$\frac{dG(t)}{dt} = -\frac{1}{T}\left(G(t)V_2^{\,2}(t) - 1\right) \quad , \quad G(0) = 1 \qquad (6)$$

Ihara, Tomiyama et al. (IEEE 1999)

Load Modeling ①





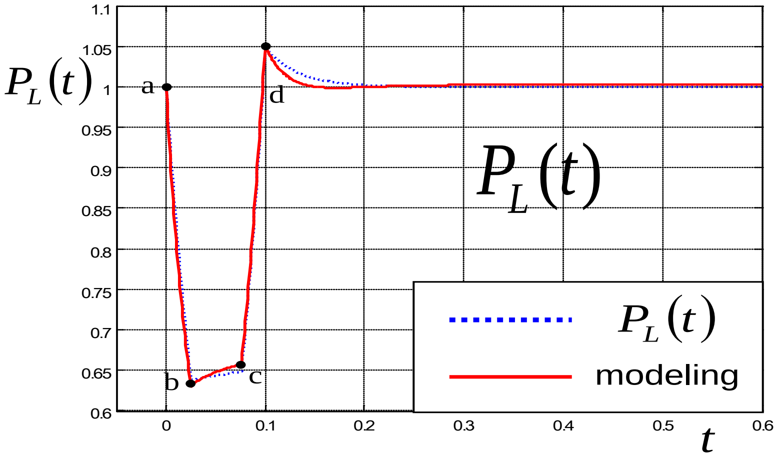


Fig. 4 Modeling of

$V_2(t)$, $P_L(t)$ and $Q_L(t)$

Load Modeling ②

Dynamic Load Model

$$\begin{cases} P_L(t) = a_0 + a_1 V_2(t) + a_2 \left(G(t) V_2^{\,2}(t) - 1 \right) & (5) \\ \dfrac{dG(t)}{dt} = -\dfrac{1}{T} \left(G(t) V_2^{\,2}(t) - 1 \right) \quad , \quad G(0) = 1 & (6) \end{cases}$$

Runge-Kutta Method

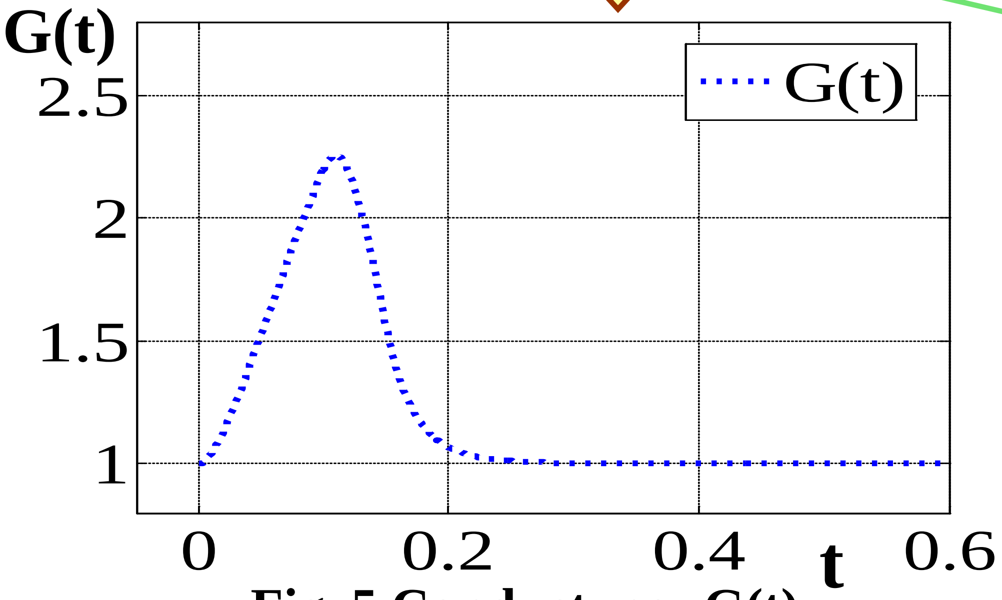


Fig. 5 Conductance G(t)

Time Constant

$$T = 0.0167$$

Load Modeling ③

Quadratic Function Model

$$G(t) \approx m + nV_2(t) + pV_2{}^2(t) \quad (7)$$

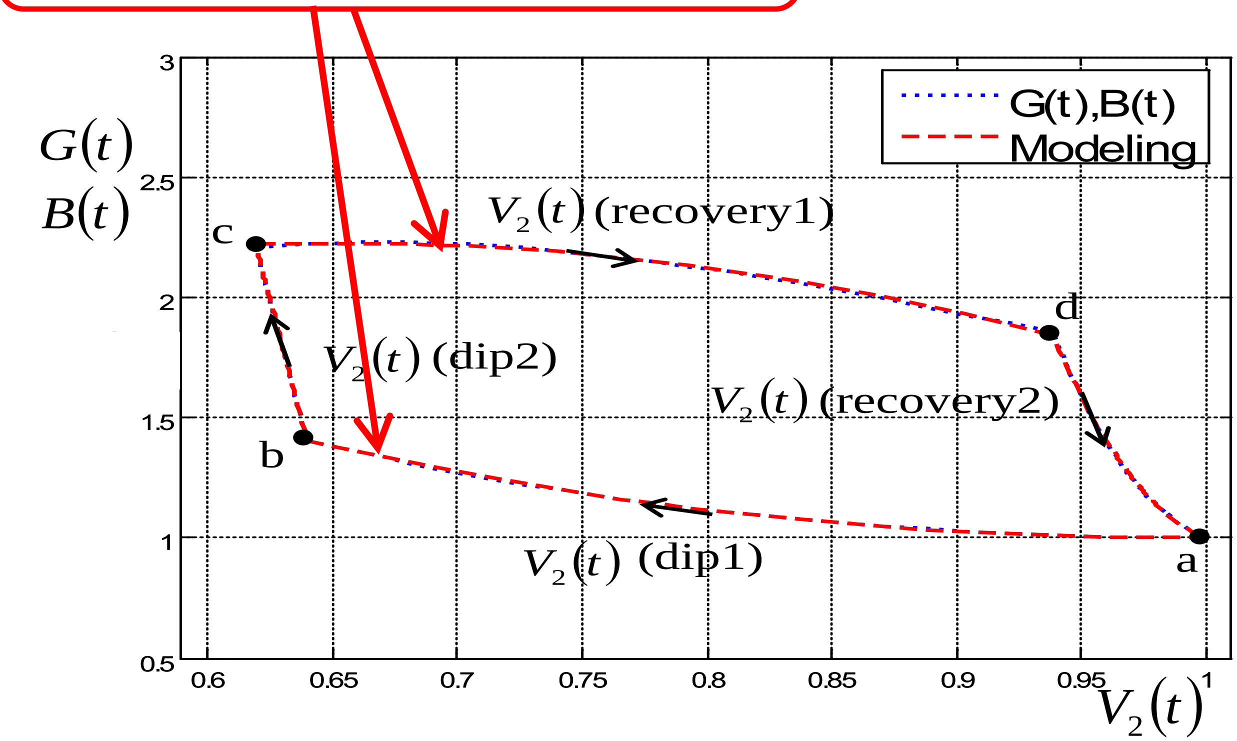


Fig. 6 Relationship between $V_2(t)$ & $G(t)$

Load Modeling ④

$$\begin{cases} P_L(t) = a_0 + a_1 V_2(t) + a_2 \left(G(t) V_2^{\,2}(t) - 1 \right) & (5) \\ \dfrac{dG(t)}{dt} = -\dfrac{1}{T}\left(G(t) V_2^{\,2}(t) - 1 \right) & (6) \end{cases}$$

$$G(t) \approx m + nV_2(t) + pV_2(t)^2 \quad (7)$$

Load P-V Curve

$$P_L = (a_0 - a_2) + a_1 V_2 + a_2 m V_2^2 + a_2 n V_2^3 + a_2 p V_2^4 \quad (8)$$

Load Q-V Curve

$$Q_L = (b_0 - b_2) + b_1 V_2 + b_2 r V_2^2 + b_2 s V_2^3 + b_2 u V_2^4 \quad (9)$$

Load P-V and Q-V Curves considering Dynamic Load

Load Modeling ⑤

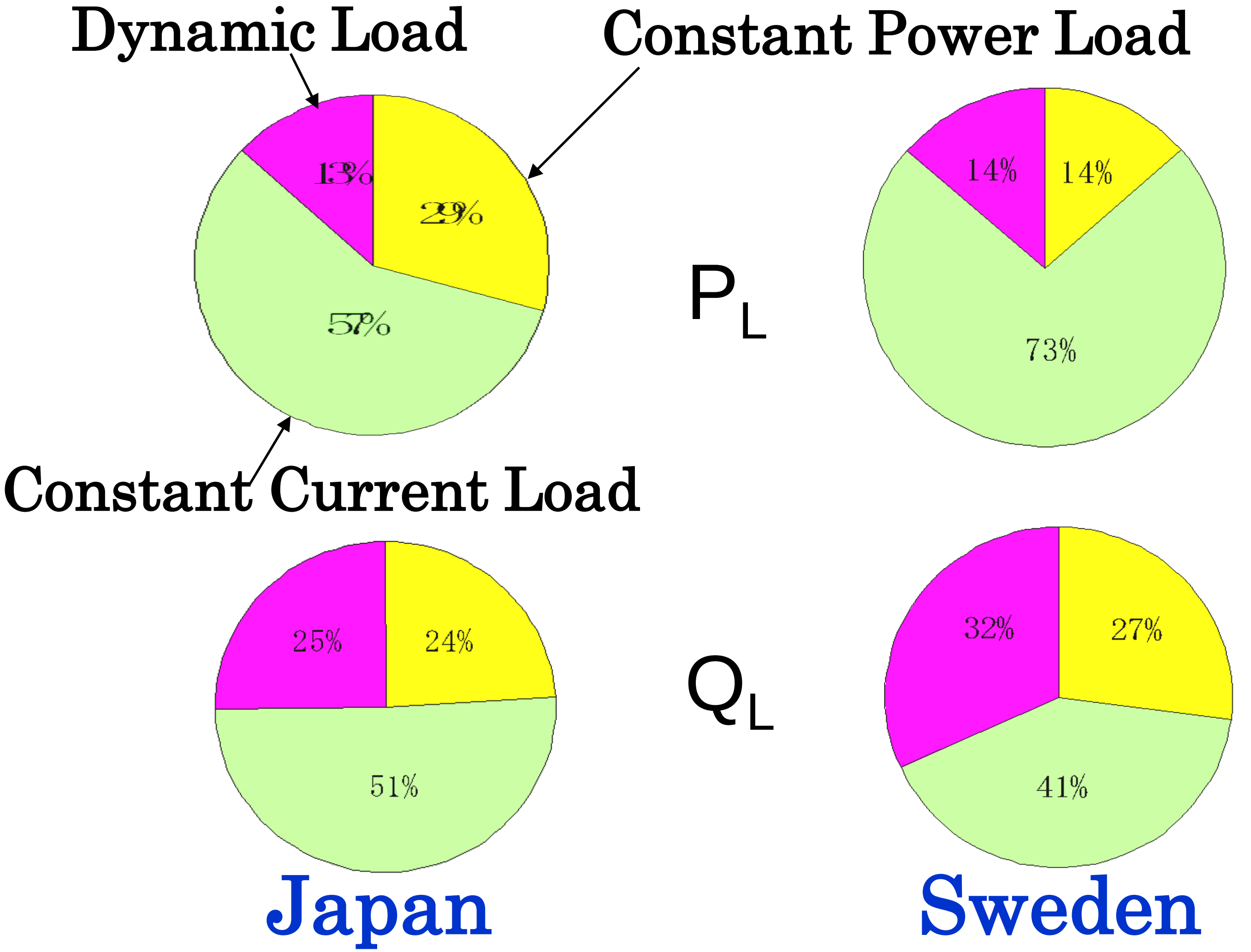


Fig. 7 Load composition

Ⅳ . Voltage Stability Analysis

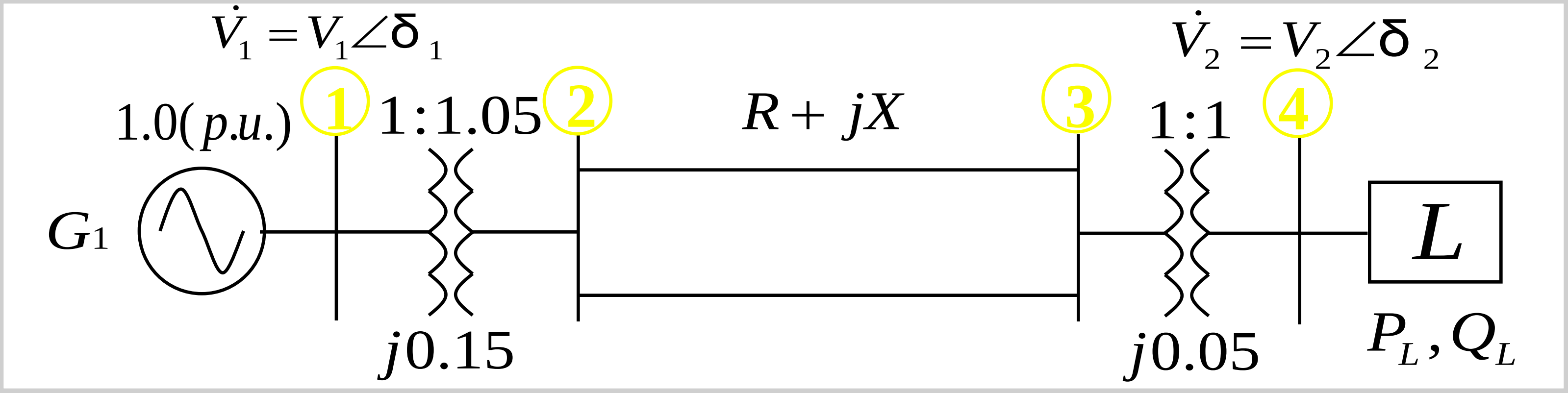


Fig. 8 The standard one-machine system model with load.

Complex Power

$$P_L + jQ_L = \dot{V}_2 \overline{\left(\frac{\dot{V}_1 - \dot{V}_2}{R_1 + jX_1}\right)} \qquad \text{(10)}$$

$$Q_L = P_L \tan\phi \qquad \text{(11)}$$

Power Factor $\cos\phi$

System P-V Curve

$$\boxed{\left(R^2 + X^2\right)\left(1 + \tan^2\phi\right)\cdot P_L^2 + 2\left(R + X\tan\phi\right)V_2^2 \cdot P_L + \left(V_2^4 - V_1^2 V_2^2\right) = 0} \qquad \text{(12)}$$

$$\left(for\ \forall\ t \geq 0\right)$$

P-V curves

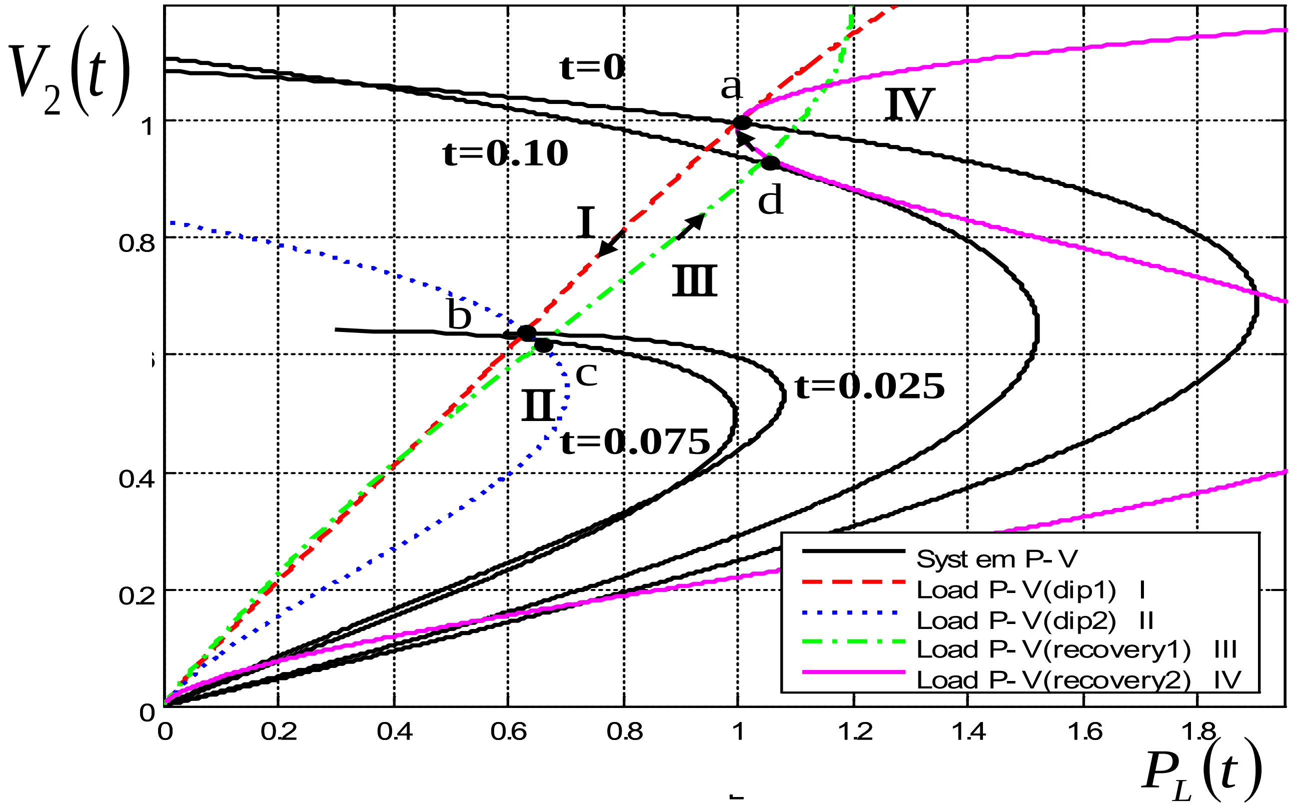


Fig. 9 System and Load P-V curves

Q-V curves

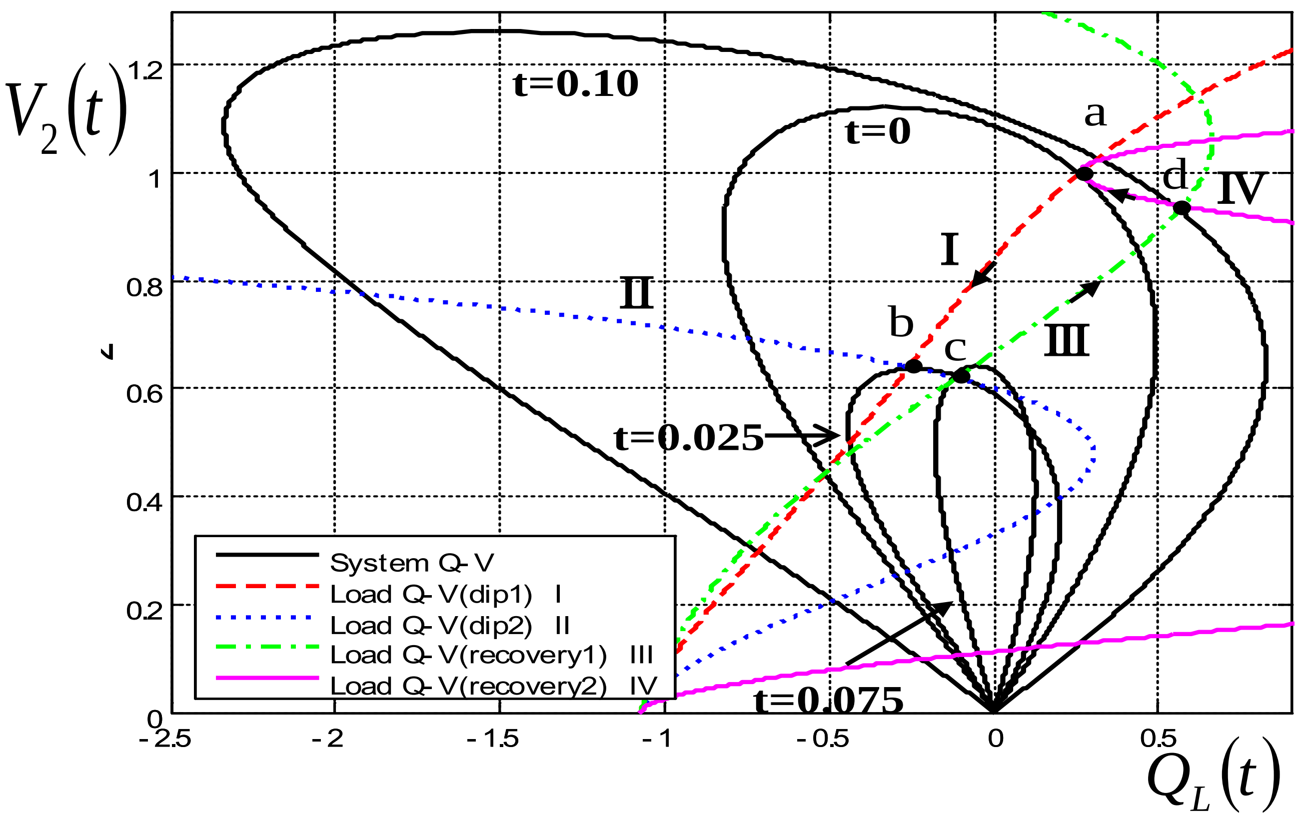


Fig. 10 System and Load Q-V Curves

Japan
Sweden

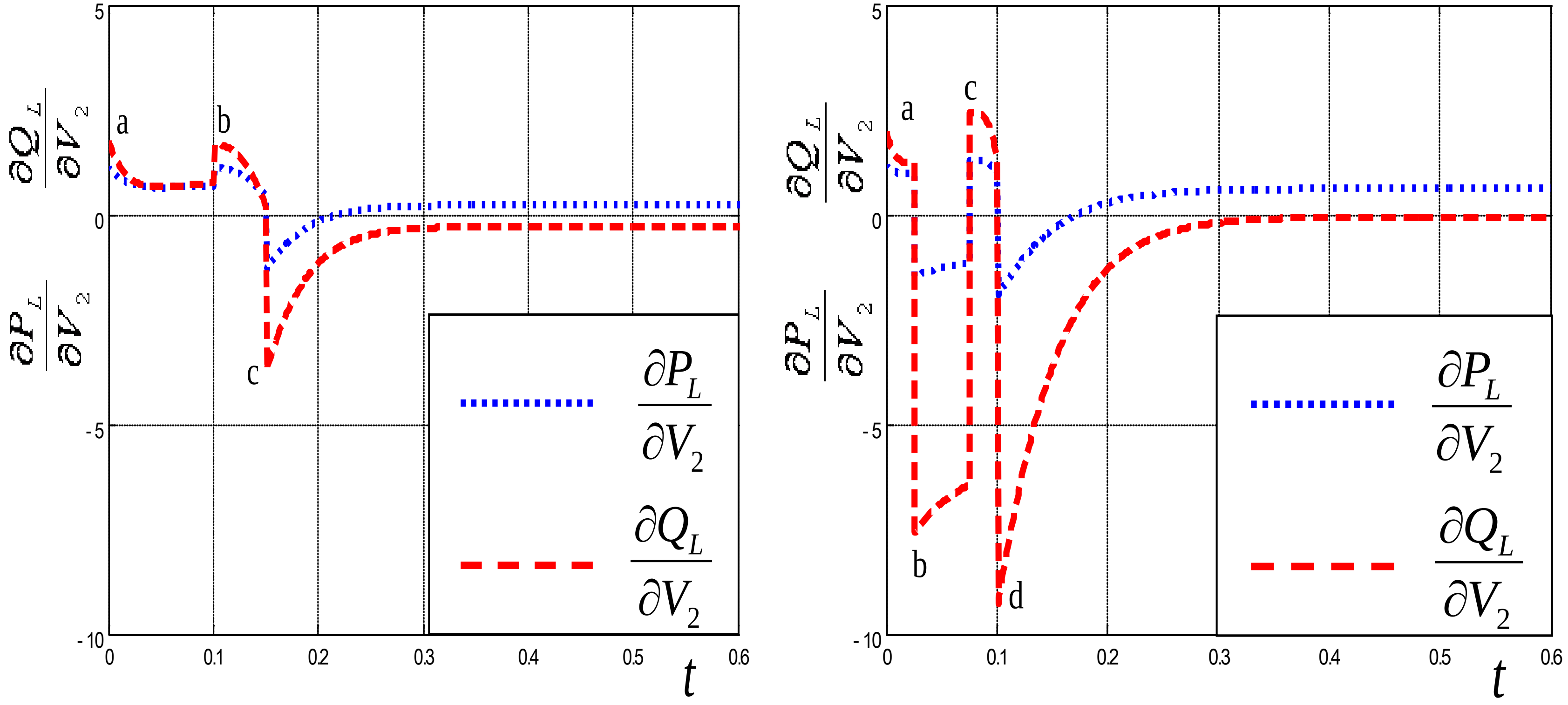
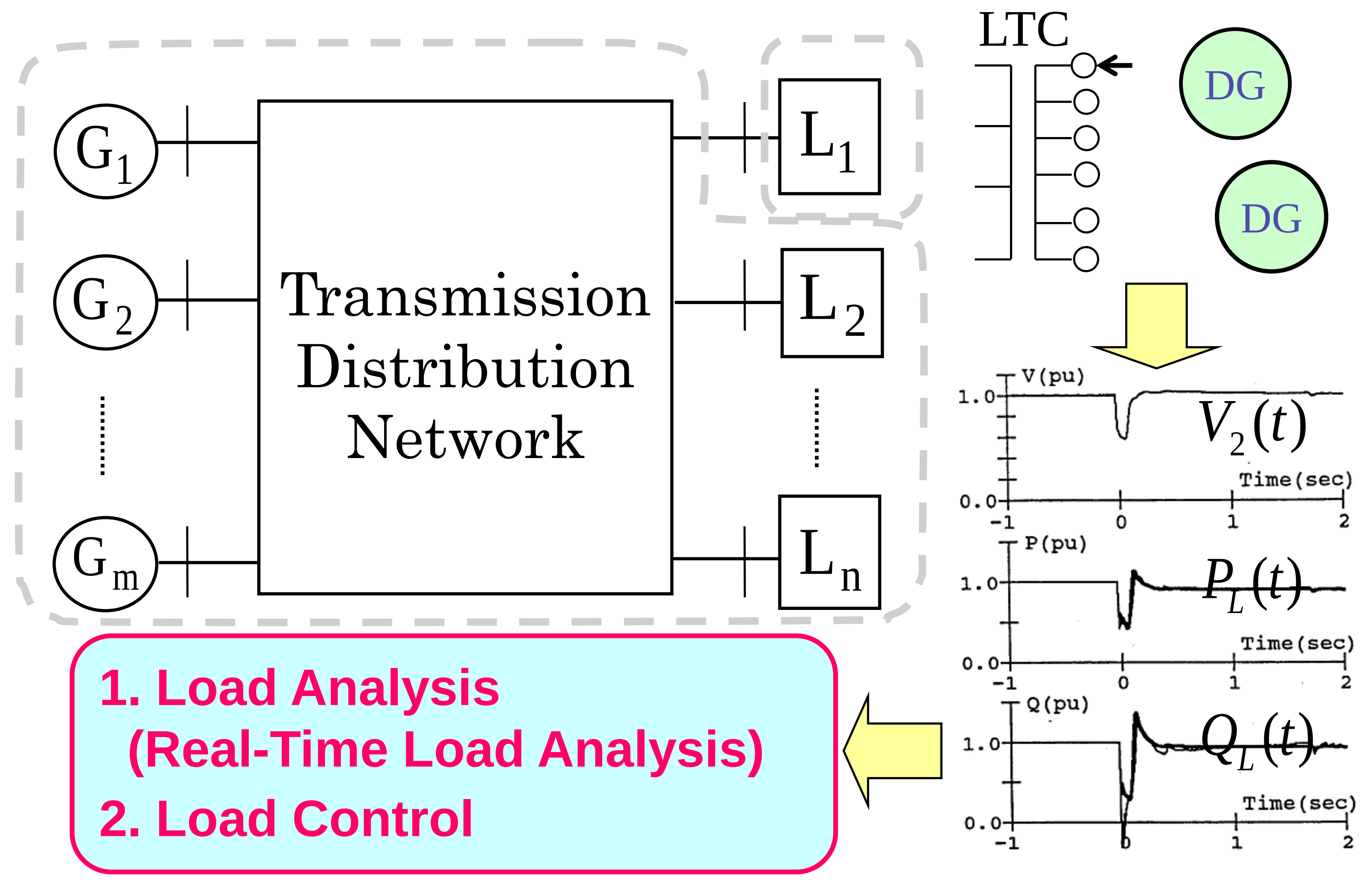


Fig. 11 Sensitivity analysis

Ⅴ. Smart Grid



1. Load Analysis
   (Real-Time Load Analysis)
2. Load Control

Ⅵ. Conclusion

(1) A power grid can be rewritten without approximation into an equivalent system at each load-bus.

(2) The dynamic load model with a differential equation can be approximated in a higher order polynomial form of V_2 .

(3) The voltage stability can be analyzed by the system and the load P-V and Q-V curves considering dynamic load.

(4) In the case of the data observed in Sweden, the reactive power is more sensitive to the voltage stability than the active one and the case of Japan.

Future Subject

Applying the proposed method to the data observed by changing LTC at sub-station, and to the load control for Smart Grid