

30th ETAP User Group

過渡安定度解析

ETAP による Industrial System Model の解析例

2019年11月26日
株式会社エルテクス設計
亀田 和之

Power System Dynamics with Computer-Based Modeling and Analysis

Yoshihide Hase, Tanuj Khandelwal, Kazuyuki Kameda
ISBN: 978-1-119-48745-6 | February 2020 | 1112 Pages

PRINT
Starting at just \$200.00

Hardcover Pre-order **\$200.00**

ABOUT THE AUTHOR

Yoshihide Hase is power systems engineering consultant in Japan.

Tanuj Khandelwal is CTO and Senior Principal Electrical Engineer at ETAP - Operation Technology, Inc. in the USA.

Kazuyuki Kameda does engineering and consulting for Electrical and Control Systems at Eltechs Engineering & Consulting Co., Ltd, in Japan.

Wiley New Book (Wiley 新刊紹介)

Power System Dynamics with Computer Based Modeling & Analysis

by Y.Hase, T.Khandelwal and K.Kameda

Experience + ETAP Solved Examples = Best Practices including IEEE & IEC

by Hase Wiley 2nd ed 2013
by Hase Maruzen 3rd ed 2015

Wiley 1112 pages!
(will be published on February 2020)

Part A: Power Systems Engineering Theories
Part B: Computational Methodologies
Part C: ETAP Examples & Analysis (ETAP Practices)

Table of Contents

Part A - Power Systems Theories and Practices

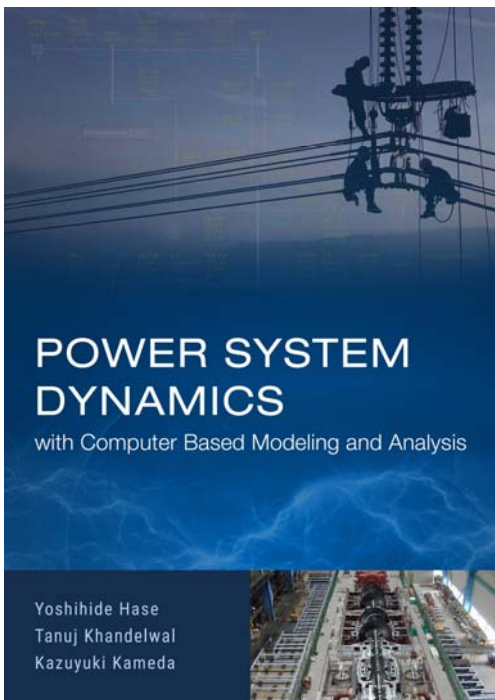
- Chapter 1 Essentials of Electromagnetism
- Chapter 2 Complex number Notation (Symbolic Method) and Laplace transform
- Chapter 3 Transmission Line Matrices and Symmetrical Components
- Chapter 4 Physics of Transmission Line and the Line Constants
- Chapter 5 Per Unit Method
- Chapter 6 Transformer Modeling
- Chapter 7 Fault Analysis based on Symmetrical Components
- Chapter 8 Fault Analysis by aB0 Method
- Chapter 9 Power Cable
- Chapter 10 Synchronous Generator: Part1 - Circuit Theory
- Chapter 11 Synchronous Generator: Part2 - Characteristics as Machinery
- Chapter 12 Steady State/Transient/Dynamic Stability
- Chapter 13 Induction Generator And Motor (Induction Machine- IM)
- Chapter 14 Directional Distance Relay and R-X Diagram
- Chapter 15 Lightning /Switching Surge Phenomena and Breaker Switching
- Chapter 16 Over-voltage Phenomena
- Chapter 17 Insulation Coordination
- Chapter 18 Harmonics and Waveform Distortion
- Chapter 19 Power Electronics Applications Part1 Devices
- Chapter 20 Power Electronics Application Part2 : Circuit Theory
- Chapter 21 Power Electronics Applications Part3 Control Theory

Part B - Digital Computations Theories

- Chapter 22 Digital Computation Basics
- Chapter 23 Power Flow Methods
- Chapter 24 Short Circuit Methods
- Chapter 25 Harmonics
- Chapter 26 Reliability
- Chapter 27 Numerical Integration Methods
- Chapter 28 Optimization

Part C - Analytical Practices and Examples

- Chapter 29 Introduction
- Chapter 30 One-Line Diagram
- Chapter 31 Load Flow
- Chapter 32 Short Circuit / Fault Analysis
- Chapter 33 Motor Starting
- Chapter 34 Harmonics
- Chapter 35 Transient Stability
- Chapter 36 Reliability Assessment
- Chapter 37 Protective Device Coordination



Part C - Analytical Practices and Examples

- Chapter 29 Introduction
- Chapter 30 One-Line Diagram
- Chapter 31 Load Flow
- Chapter 32 Short Circuit / Fault Analysis
- Chapter 33 Motor Starting
- Chapter 34 Harmonics
- Chapter 35 Transient Stability
- Chapter 36 Reliability Assessment
- Chapter 37 Protective Device Coordination

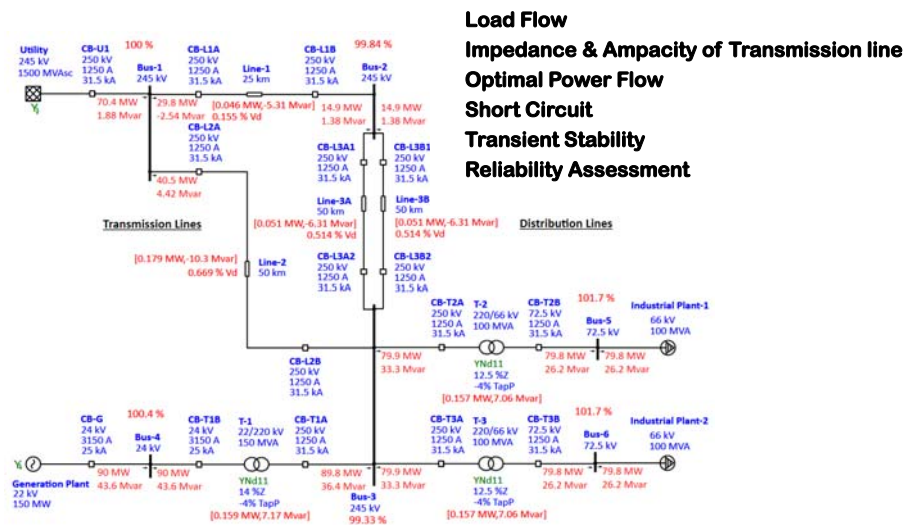
POWER SYSTEM DYNAMICS
with Computer Based Modeling and Analysis

Yoshihide Hase
Tanuj Khandelwal
Kazuyuki Kameda

Example Project
Transmission System
Industrial System
Renewable Energy System

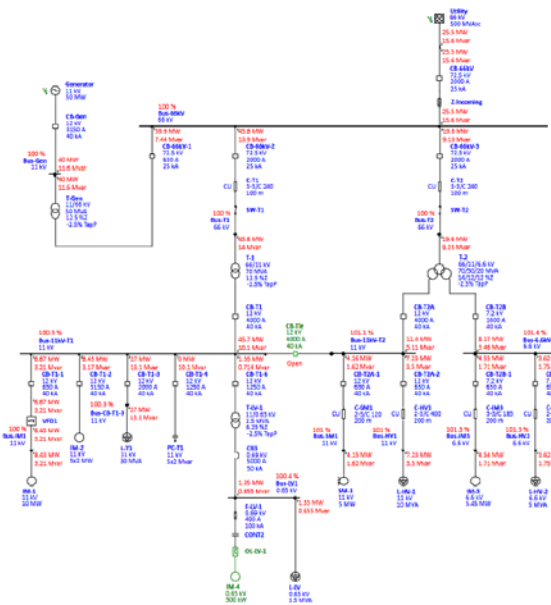
過渡安定度解析 - ETAP による Industrial System Model の解析例

Transmission System



過渡安定度解析 - ETAP による Industrial System Model の解析例

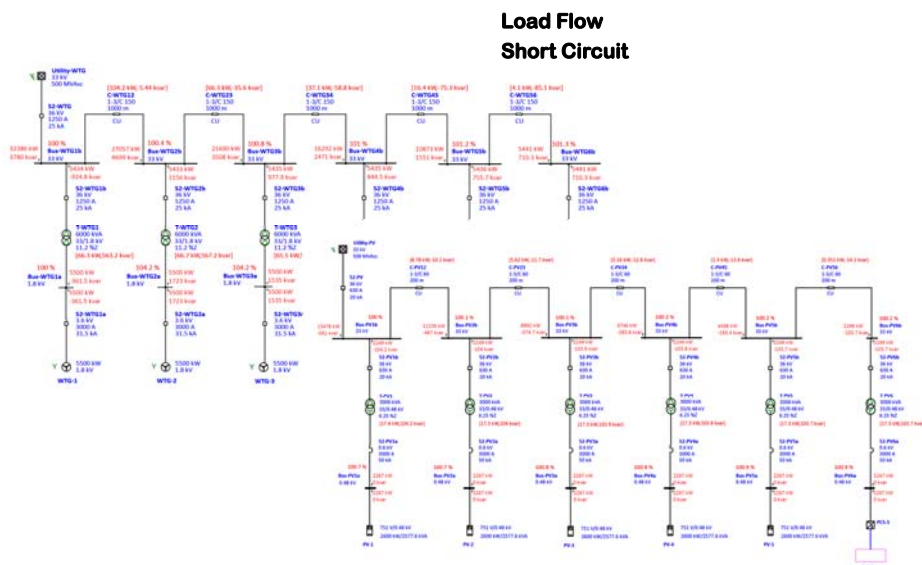
Industrial System



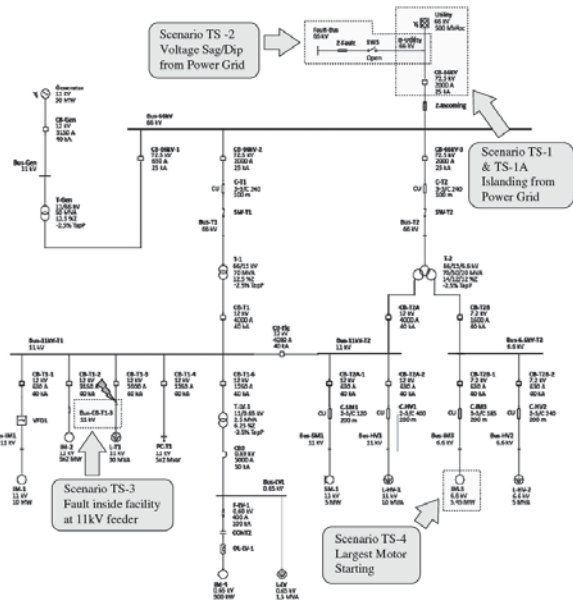
- Load Flow
- Cable Ampacity & Cable Sizing
- Underground Cables
- Short Circuit
- Grounding Grid System
- Motor Starting
- Harmonic
- Transient Stability

過渡安定度解析 - ETAP による Industrial System Model の解析例

Renewable Energy System



- Load Flow
- Short Circuit



Industrial System Transient Stability

解析項目

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

商用系統、母線、変圧器のデータ

Power grid	
Operating mode	Swing
Nominal kV	66 kV
Short-circuit capacity	500 MVA
X/R ratio	20

Buses (nodes)	
Nominal kV	66 kV, 11 kV, 6.6 kV, 0.65 kV

Transformers

- Two-winding transformer

ID	Rated kV		MVA	%Z	X/R	Connection	Grounding	Tap
	Primary	Secondary						
T-Gen	11	66	50	12.5	45	YNd11	Solid	As per required
T-1	66	11	70	12.5	45	Dyn11	Solid	
T-LV-1	11	0.65	2.5	6.25	6	Dyn11	Solid	

- Three-winding transformer

ID	Winding	Rated kV	MVA	%Z	X/R	Connection	Grounding	Tap
	Secondary	11	50	12 ^a	40	Delta		
	Tertiary	6.6	20	12 ^c	40	Delta		

^a Primary-secondary.
^b Primary-tertiary.
^c Secondary-tertiary.

電力潮流計算に必要なデータ

- 潮流計算に必要なデータを入力する。
- 潮流計算を実行する。
- 初期潮流のチューニング（事故・系統動揺が起こる前の電力潮流状態）

負荷データ（誘導電動機、同期電動機、一括負荷）

Loads

- Induction motor

Motor ID	MW	Pole	kV	% Load	LRC (%)	PF Ir (%)	LRTq (%)	MaxTrq (%)	Slip (%)	PF (%)	Eff (%)	Current (A)	Qty.
IM-1	10	4	11	80	650	7.59	35.29	220.8	1.5	93.44	94.92	591.8	1
IM-2	2	4	11	80	650.08	15.05	99.65	220.2	1.5	93.2	95.45	118	5
IM-3	5.45	4	6.6	80	549.9	20.01	65.02	165	1.5	92.06	95.55	542	1
IM-4	300	4	0.65	100	600	20.06	35	210	0	91.99	93.11	311.1	1

- Synchronous motor

Motor ID	MW	Pole	kV	% Load	LRC (%)	PF Ir (%)	PF (%)	Eff (%)	Current (A)	Quantity
SM-1	5	2	11	80	650	9.2	93.15	96.3	292.6	1

- Lumped loads

Lumped Load ID	MVA	kV	PF (%)	%Motor Load	%Static Load	LRC (%)	X/R	% Load
L-HV-1	10	11	90	80	20	600	10	80
L-HV-2	5	6.6	90	80	20	600	10	80
L-LV	1.5	0.65	90	80	20	600	2.38	100
L-T1	30	11	90	80	20	650	10	100

発電機、電力コンデンサ、ケーブルのデータ

Synchronous generator

Operating mode	Voltage control
Rating	50 MW, 11 kV, 2 poles, %PF = 90, %Eff. = 98%
Generation	40 MW, %V = 100%
Subtransient impedance	$X_d'' = 25\%$
Transient reactance	$X_d' = 35\%$
Synchronous reactance	$X_d = 99\%$
X/R ratio	$X''d/Ra = 25$

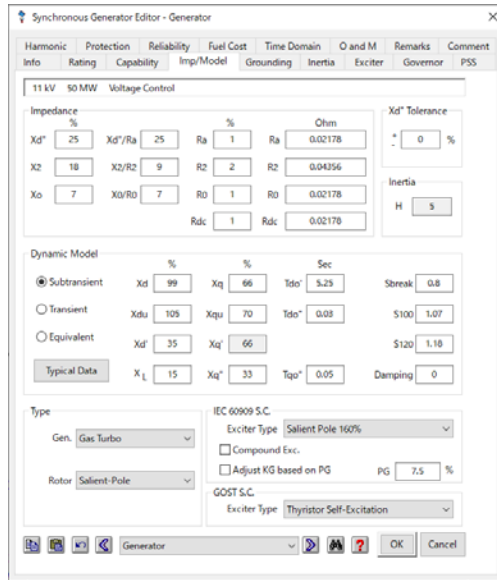
- Power capacitors

Nominal kV	11 kV
Capacity	2Mvar × 5 banks

- Feeder cables

Cable ID	Voltage (kV)	Type	Core	Size (mm ²)	Qty	Length (m)
C-T1	66	XLPE	3	240	3	100
C-T2	66	XLPE	3	240	3	100
C-SM1	11	XLPE	3	120	2	200
C-HV1	11	XLPE	3	400	2	200
C-IM3	6.6	XLPE	3	185	3	200
C-HV2	6.6	XLPE	3	240	2	200

発電機定数 (初期過渡定数 : Subtransient)

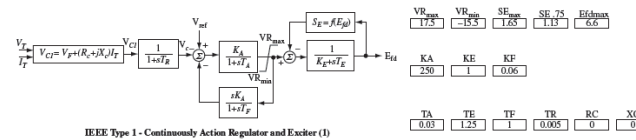


過渡安定度計算に必要なデータ

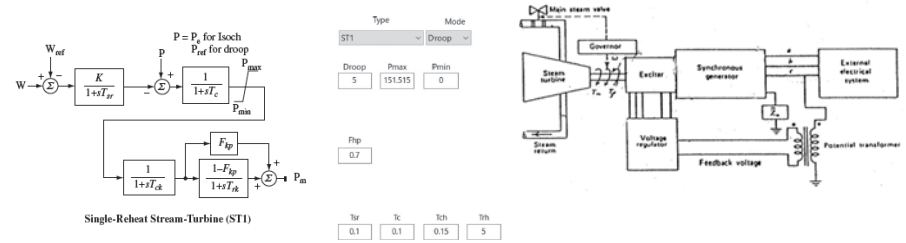
- 過渡安定度計算に必要なデータを追加入力する。
- 発電機定数 (初期過渡定数 : Subtransient)
- AVR, Governor, PSS
- 慣性定数
- 電動機のダイナミックモデリング

AVR (IEEE Type 1), Governor (ST1), Inertia (H)

• AVR model => IEEE Type 1:



• Governor model => ST1 model:



• Inertia of generator and prime mover:

H = 2 MW-s/MVA (WR2 = 6751 kg/m²) total for the generator and prime mover.

誘導電動機 (5450kW, 4 pole) のダイナミックモデリング

Starting Motor Data

Output 5.45 MW
Poles 4
Load Fan
Motor Torque, Current, Power Factor Curve (Estimate based on the motor parameters below.)

- LRC (%) 550
- PF100 (%) 20
- T1r (%) 65
- Tmax (%) 165
- Slip (%) 1.5
- PF100 (%) 92.1
- EFF100 (%) 95.54

Inertia WR² = 500 kg-m² (motor and fan)

Parameters for motor
(Locked rotor current/power factor/ torque, Full load slip/current/torque/power and factor/efficiency)

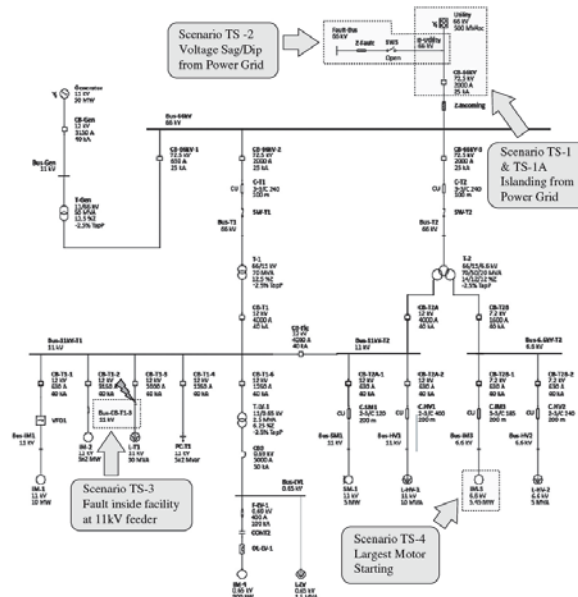
Locked Rotor		Full Load	
Input	Output	Input	Output
550	20	64.95	165
0.01	0.01	0.01	0.01

Estimated equivalent circuit

Estimated parameters for motor equivalent circuit

R1	X1	Xm	R2	X2	Xr	Rr	Ry	Rf
1.717	17.802	1090.067	8378.52	0.01	14.013	1.921	1.435	

Estimated motor torque, current and power factor curve



Industrial System Transient Stability

解析結果

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

Table 35.4 Summary of transient-stability analysis for an industrial system.

Scenario	Event/Action/Results/Countermeasures
Industrial plant islanding from power grid	
TS-1	<p>Event 1: Islanding the system from power grid => Action: open CB-66kV at 0.1 sec.</p> <p>Results: Generator speed falls, and mechanical power reaches up to 50 MW (generator rated power) => Generator trips, and the system will collapse.</p>
TS-1A	<p>Countermeasure Load shed (trip L-T3 [30MVA] after 0.2 sec from Event 1)</p> <p>Event 1: Islanding the system from power grid => Action: open CB-66kV at 0.1 sec.</p> <p>Event 2: Load shedding after 0.2 sec from Event 1 (trip L-T3, 30 MVA) => Action: open CB-T1-3 at 0.3 sec.</p> <p>Results: Both generator speed and mechanical power returned to stable conditions.</p>

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

- TS-1**
- Event 1:
- ✖ 商用停電
- Action 1:
- ✖ Open CB-66kV at 0.1sec.
- Results:
- ✖ 発電機速度喪失
 - ✖ 機械出力飽和

- TS-1A**
- Event 1:
- ✖ 商用停電
- Action 1:
- ✖ Open CB-66kV at 0.1sec.
- Event 2:
- ✖ 負荷選択遮断 (50MW)
- Action 2:
- ✖ Open CB-T1-3 at 0.3sec.
- Results:
- ✖ 発電機速度回復
 - ✖ 機械出力回復

Scenario	Event/Action/Results/Countermeasures
Voltage sag/dip from power grid	
TS-2	<p>Event 1: Voltage sag/dip (down to 20% for 0.2 sec) occurred in power grid, and the voltage at Bus-66kV fell to 20% => Action: fault at Fault-Bus at 0.1 sec.</p> <p>Event 2: Voltage at Bus-66kV returns to 100% after 0.2 sec from Event 1 => Action: clear fault at 0.3 sec.</p> <p>Results: Voltage of the 66kV bus (Bus-66kV) falls to 20% for 0.2 sec Voltage of the 11kV bus (Bus-11kV-T1) also falls to approx. 20% for 0.2 sec Although the speed and power angle of the generator fluctuate somewhat, they return to a stable state within approx. 20 seconds. The synchronous motor SM-1 (5MW) also returns to a stable state within approx. 2 seconds. The industrial plant will continue operation even with the voltage sag/dip at the grid (falls to 20% for 0.2 sec).</p>

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

- TS-2**
- Event 1:
- ✖ 商用瞬低
- Action 1:
- ✖ 66kV受電母線電圧が、2秒間20%に低下
- Results:
- ✖ 66kV母線電圧 => 回復
 - ✖ 11kV母線電圧 => 回復
 - ✖ 発電機速度 => 回復
 - ✖ 発電機位相 => 回復
 - ✖ 同期電動機速度 => 回復
 - ✖ 同期電動機位相 => 回復

Scenario	Event/Action/Results/Countermeasures
Fault inside plant at 11kV feeder	
TS-3	<p>Event 1: Short-circuit fault at 11kV bus (Bus-CB-T1-3) => Action: fault at Bus-CB-T1-3 at 0.1 sec.</p> <p>Event 2: Clear fault after 0.2 sec from Event 1 => Action: clear fault at 0.3 sec.</p> <p>Results: Voltage of the 66kV bus (Bus-66kV) falls to approx. 50% for 0.2 sec Voltage of the 11kV bus (Bus-11kV-T1) falls to 0% for 0.2 sec due to bolted (zero-impedance) fault near this bus Although the speed and power angle of the generator fluctuate somewhat, it returns to a stable state within approx. 20 seconds. The synchronous motor SM-1 (5 MW) also returns to a stable state within approx. 2 seconds. The industrial plant will continue operation if it is cleared within 0.2 sec against a short-circuit fault occurring on the 11kV bus (Bus-CB-T1-3).</p>

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

- TS-3**
- Event 1:
- ✖ 11kV母線短絡
- Action 1:
- ✖ 母線 Bus-CB-T1-3 で3相短絡事故, at 0.1sec.
- Event 2:
- ✖ 0.2秒後に事故解除
- Action 2:
- ✖ 事故解除, at 0.3sec.
- Results:
- ✖ 66kV母線電圧 => 回復
 - ✖ 11kV母線電圧 => 回復
 - ✖ 発電機速度 => 回復
 - ✖ 発電機位相 => 回復
 - ✖ 同期電動機速度 => 回復
 - ✖ 同期電動機位相 => 回復

Scenario	Event/Action/Results/Countermeasures
Largest motor starting	
TS-4	<p>Event 1: Start the largest-capacity motor IM-3 (5.45 MW) => Action: start IM-3 at 0.1 sec.</p> <p>Results: Starting time is approx. 0.9 sec from induction machine slip curve. Bus voltage at starting the motor falls to 95% at Bus-66kV-T2 and 95% at Bus-66kV. The largest-capacity motor (IM-3, 5.45 MW) can start in a reasonable amount of time when the plant is running on the system configuration "11 kV CB-Tie Open" case.</p>

- TS-1 商用停電
- TS-2 商用瞬低
- TS-3 母線短絡
- TS-4 電動機始動

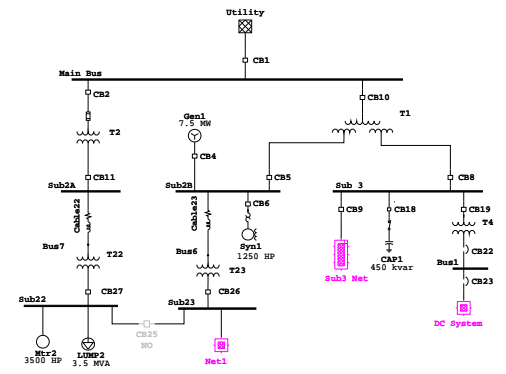
- TS-4**
- Event 1:
- ✖ IM-3 (5.45MW) 始動
- Action 1:
- ✖ Start IM-3, at 0.1sec.
- Results:
- ✖ 電動機すべり => 9sec.
 - ✖ 加速トルク => 回復
 - ✖ 電動機端子電圧 => 90%
 - ✖ 電動機電流 => 回復
 - ✖ 66kV 母線電圧 => 95%
 - ✖ 6.6kV 母線電圧 => 92%

ETAP Workshop E100JP 過渡安定度解析



事故・系統動揺

- ⚡ 停電
- ⚡ 瞬低
- ⚡ 短絡事故
- ⚡ 系統切換
- ⚡ 発電機停止
- ⚡ 大容量電動機始動

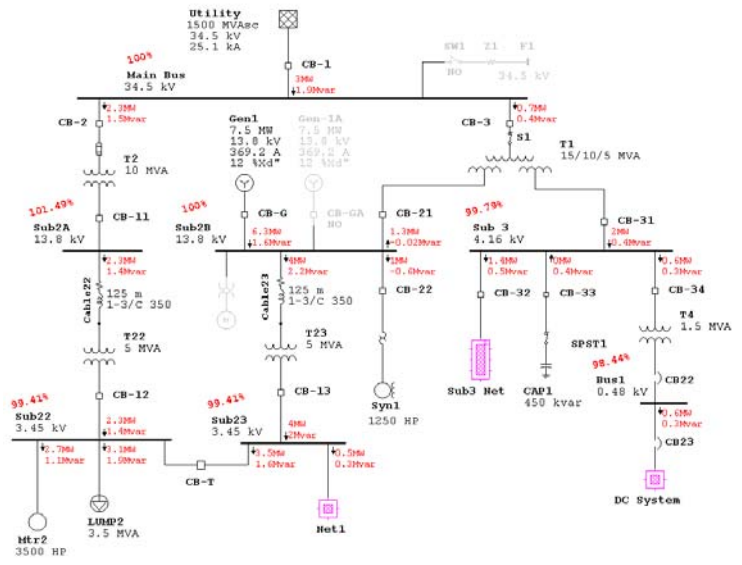


設定項目

- ⚡ イベントおよびアクションの設定
- ⚡ 保護継電器動作によるアクションの設定
- ⚡ 瞬時電圧低下現象のモデリング
- ⚡ 発電機のモデリング
- ⚡ 誘導電動機のモデリング
- ⚡ スタディケースの設定

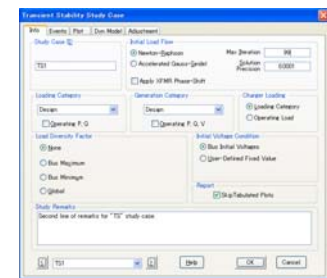
Sample Project

初期潮流のチューニング



Study Case の設定

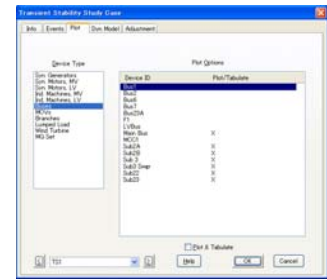
1. 初期潮流計算の設定



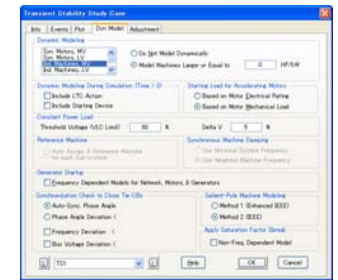
2. イベント & アクションの設定



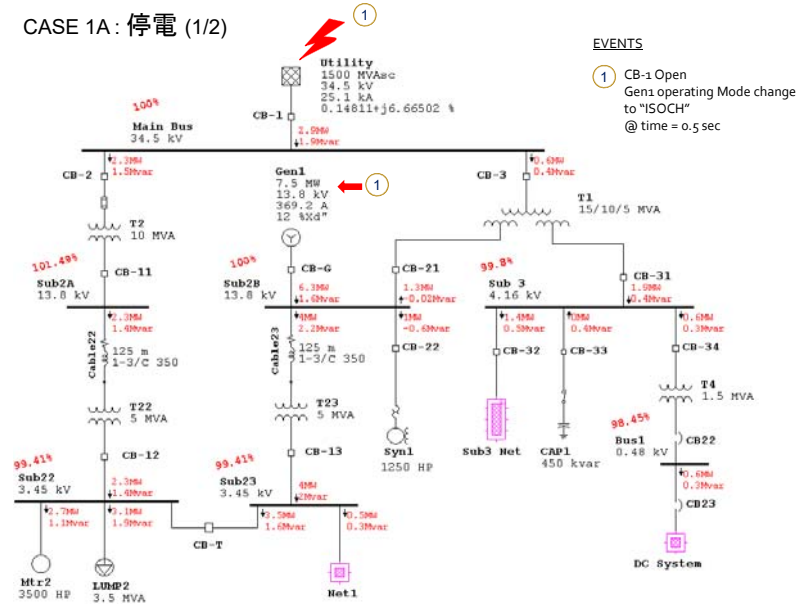
3. Plot (グラフ) の設定



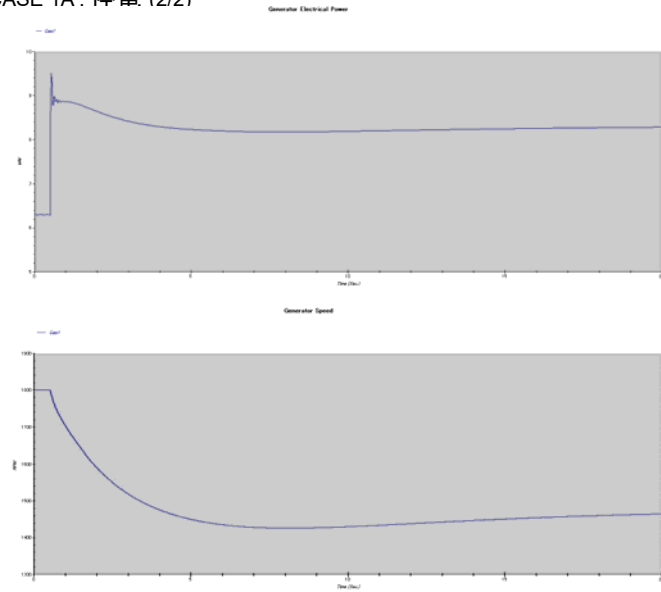
4. ダイナミックモデルの設定



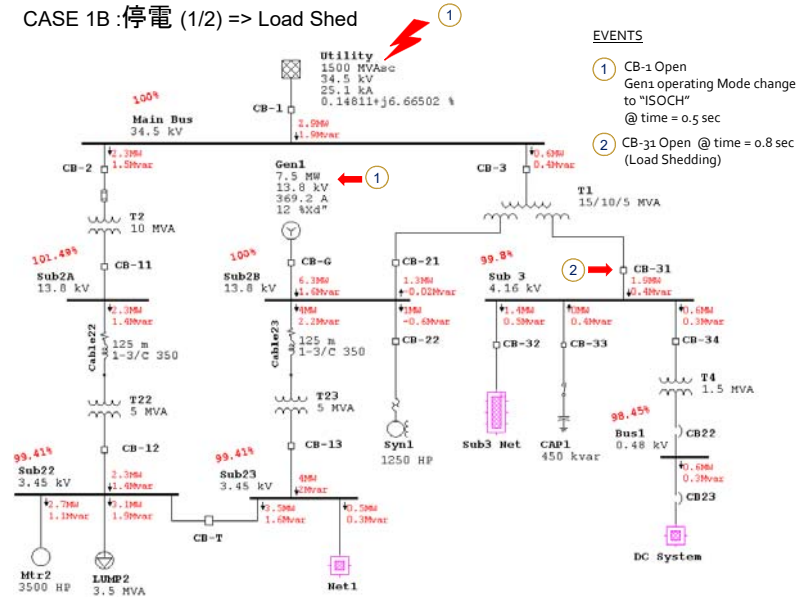
CASE 1A: 停電 (1/2)



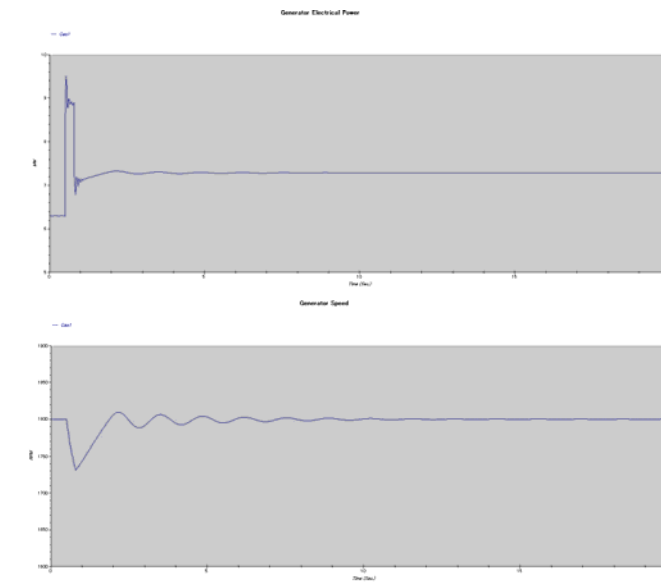
CASE 1A: 停電 (2/2)



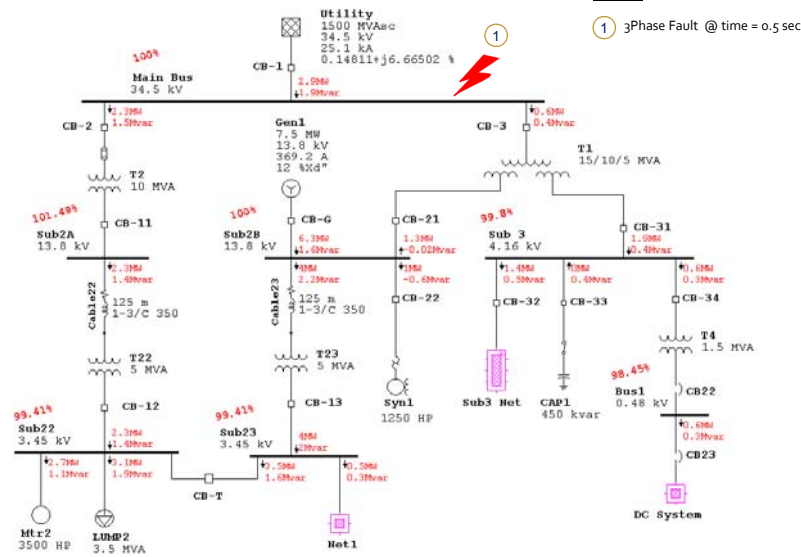
CASE 1B: 停電 (1/2) => Load Shed



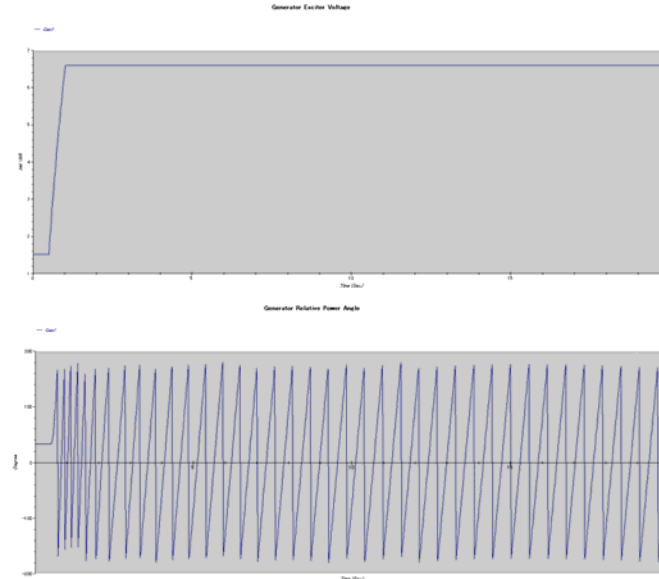
CASE 1B: 停電 (2/2) => Load Shed



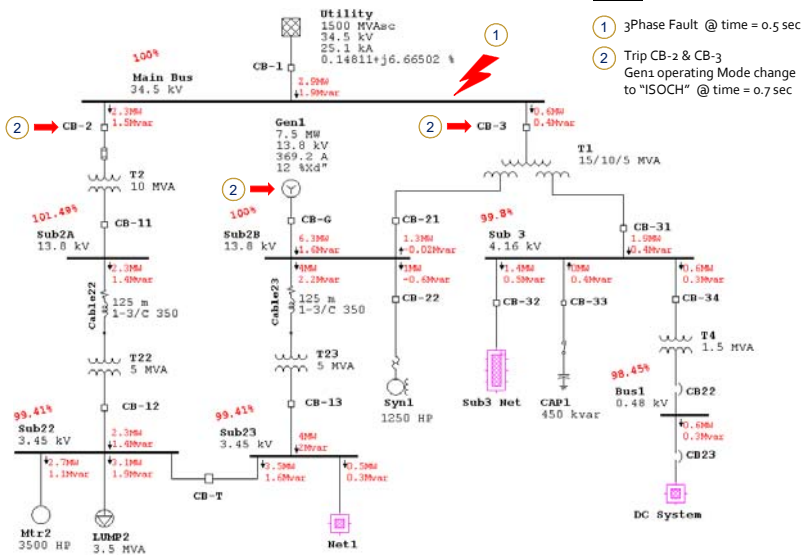
CASE 2A: 母線短絡 (1/2) => 事故継続



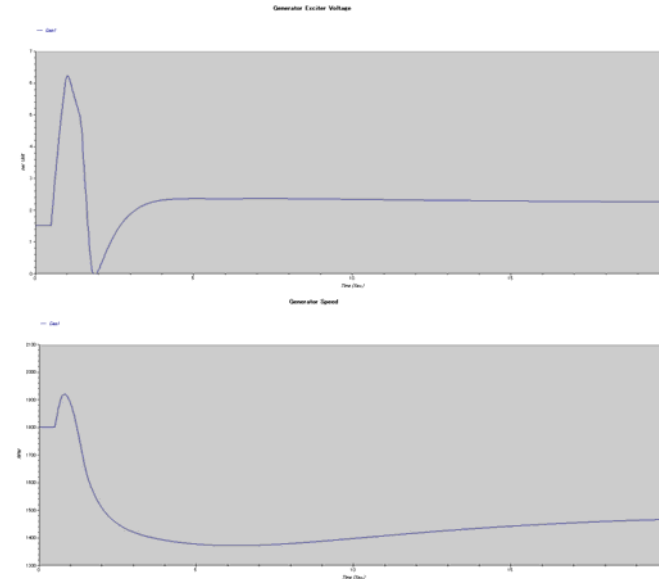
CASE 2A: 母線短絡 (2/2) => 事故継続



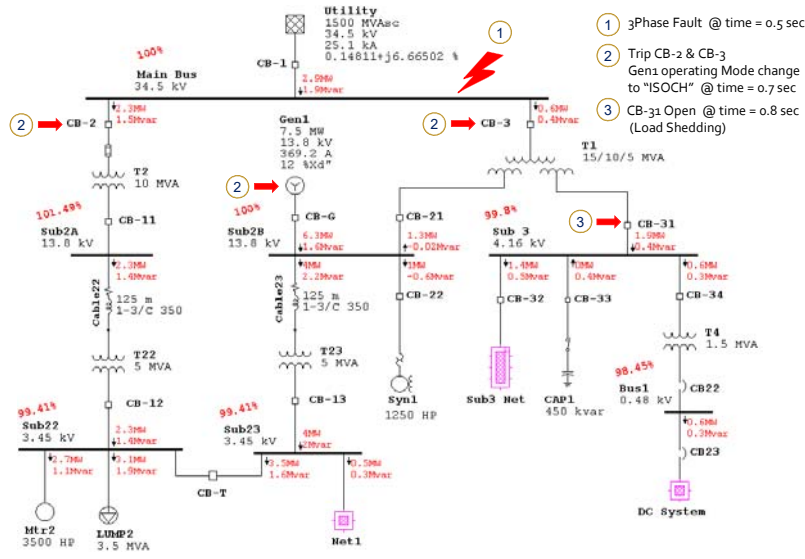
CASE 2B: 母線短絡 (1/2) => 事故解除



CASE 2B: 母線短絡 (2/2) => 事故解除

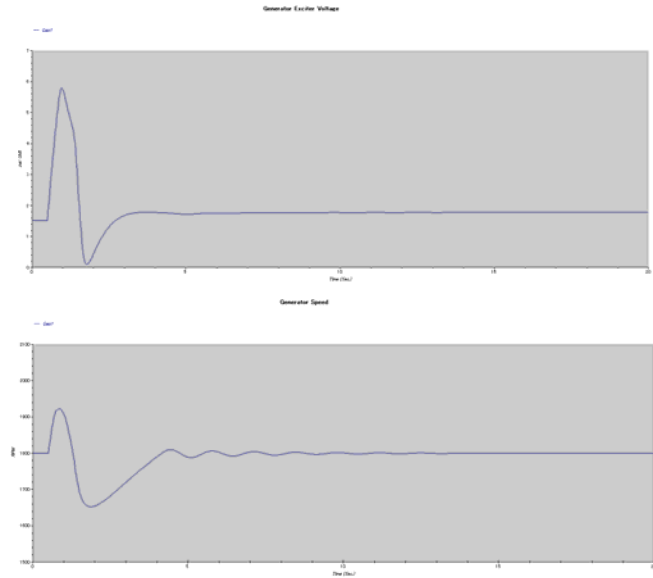


CASE 2C : 母線短絡 (1/2) => Load Shedding

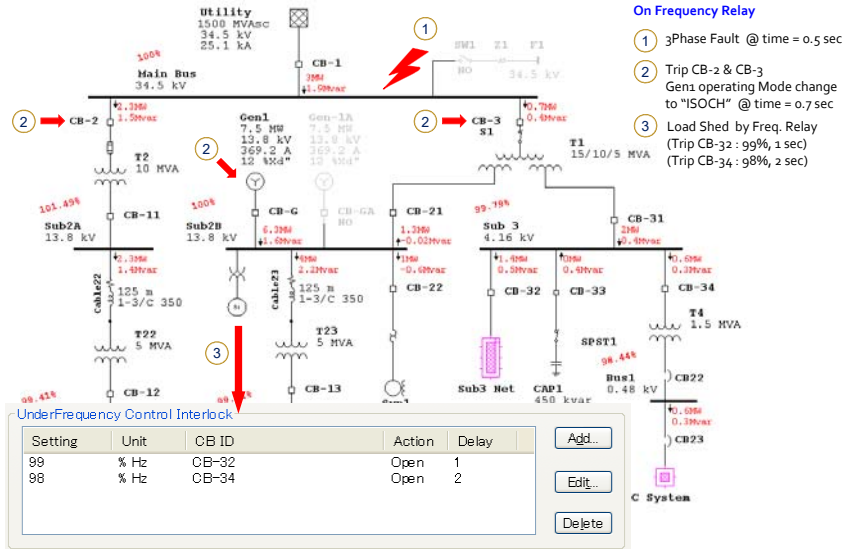


- EVENTS
- ① 3Phase Fault @ time = 0.5 sec
 - ② Trip CB-2 & CB-3
Gen1 operating Mode change to "ISOCH" @ time = 0.7 sec
 - ③ CB-31 Open @ time = 0.8 sec (Load Shedding)

CASE 2C : 母線短絡 (2/2) => Load Shedding



CASE 2D : 母線短絡 (1/2) => Load Shed by Freq. Relay



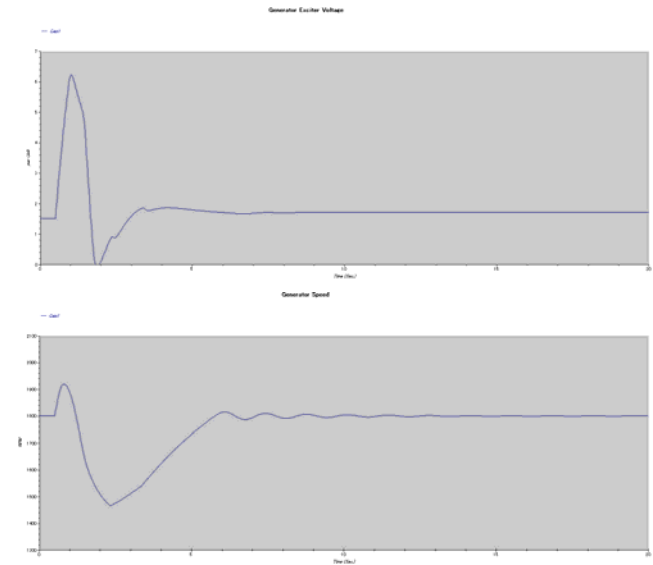
- EVENTS
- On Frequency Relay
- ① 3Phase Fault @ time = 0.5 sec
 - ② Trip CB-2 & CB-3
Gen1 operating Mode change to "ISOCH" @ time = 0.7 sec
 - ③ Load Shed by Freq. Relay
(Trip CB-32 : 99%, 1 sec)
(Trip CB-34 : 98%, 2 sec)

UnderFrequency Control Interlock

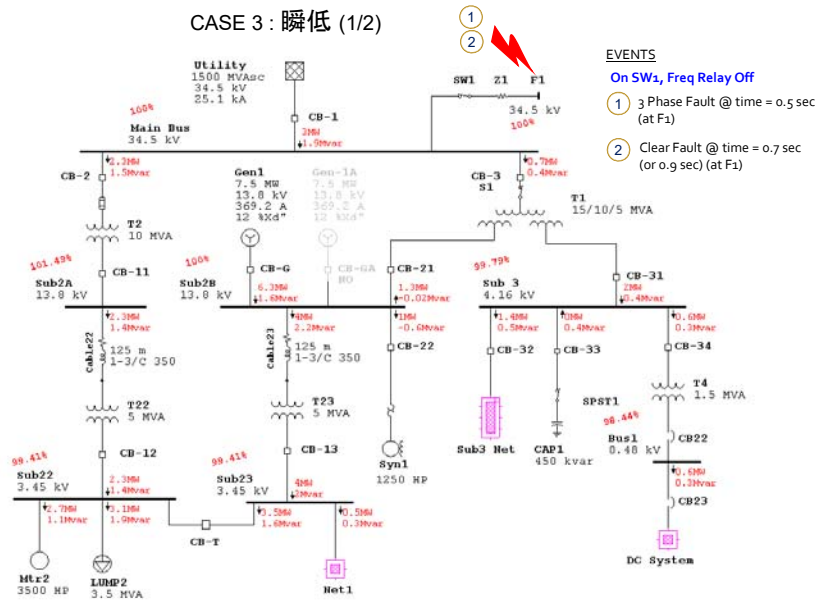
Setting	Unit	CB ID	Action	Delay
99	% Hz	CB-32	Open	1
98	% Hz	CB-34	Open	2

Buttons: Add, Edit, Delete

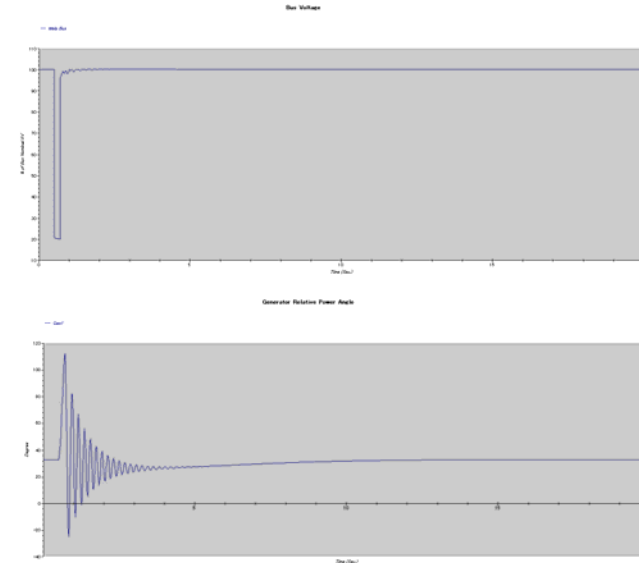
CASE 2D : 母線短絡 (2/2) => Load Shed by Freq. Relay



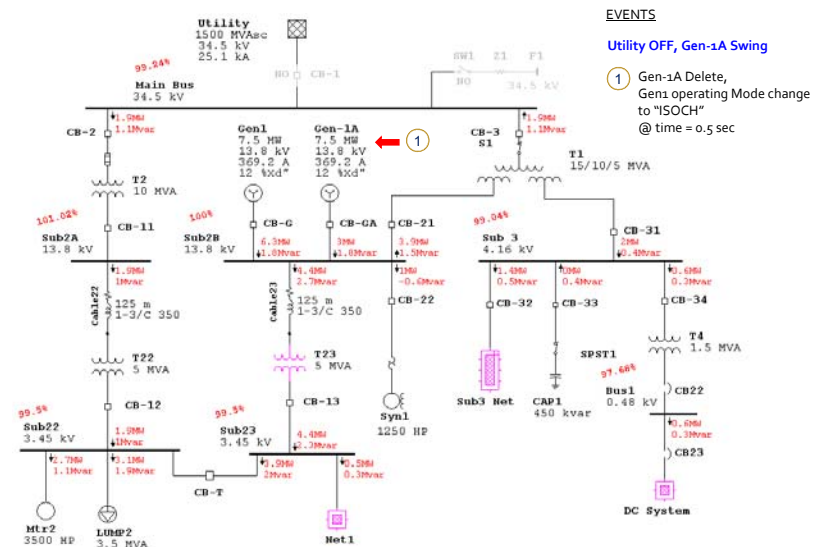
CASE 3: 瞬低 (1/2)



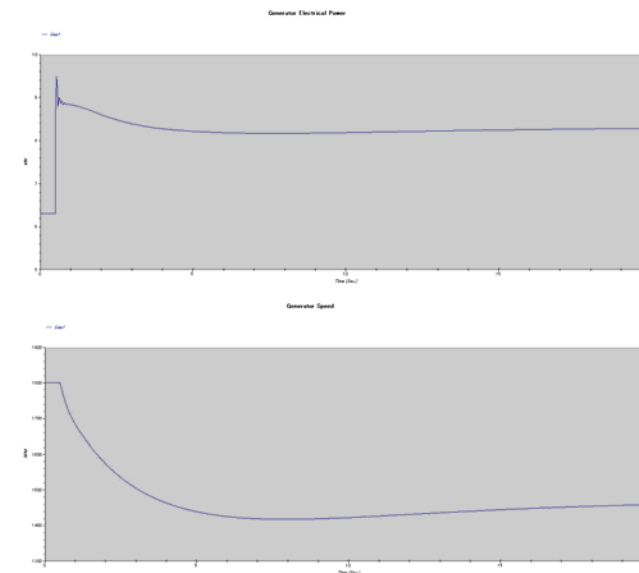
CASE 3: 瞬低 (2/2)



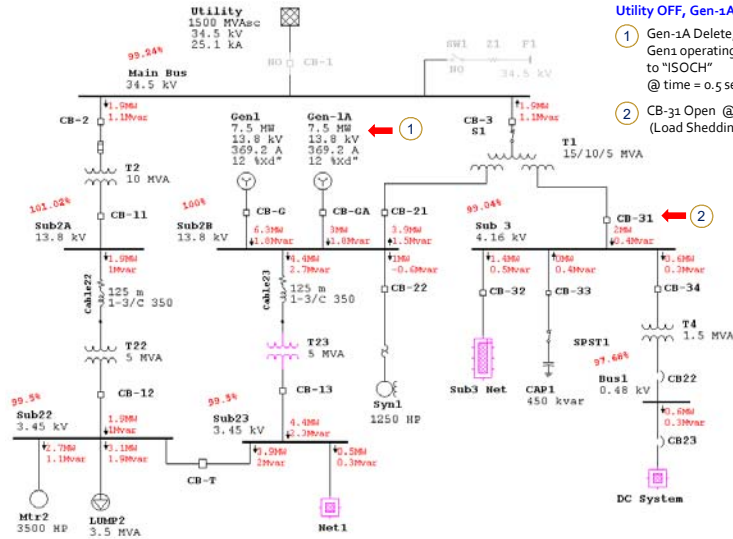
CASE 4A: 発電機停止 (1/2)



CASE 4A: 発電機停止 (2/2)

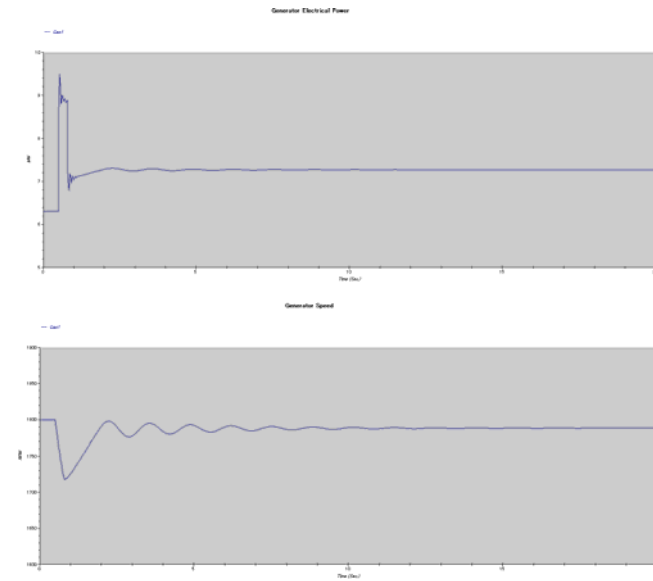


CASE 4B : 発電機停止 (1/2) => Load Shedding

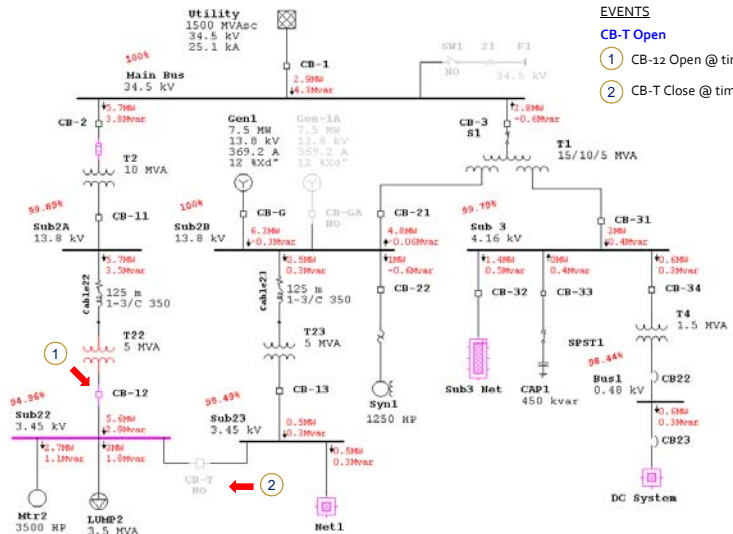


- EVENTS
- Utility OFF, Gen-1A Swing
 - ① Gen-1A Delete, Gen1 operating Mode change to "ISOCH" @ time = 0.5 sec
 - ② CB-31 Open @ time = 0.8 sec (Load Shedding)

CASE 4B : 発電機停止 (2/2) => Load Shedding

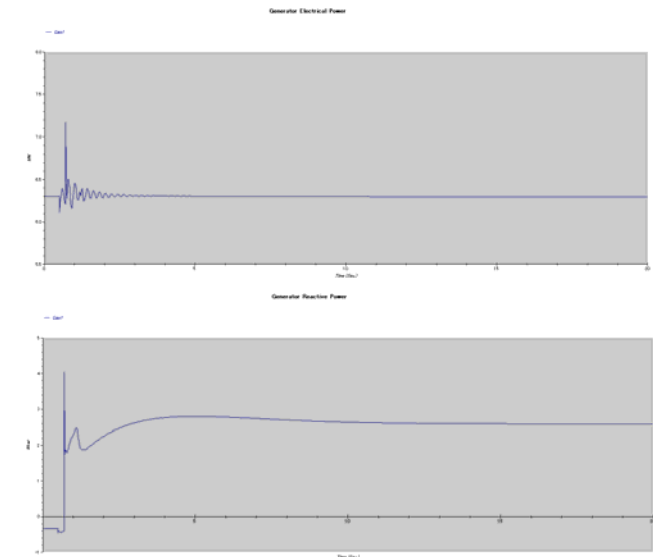


CASE 5 : 系統切換 (1/2)

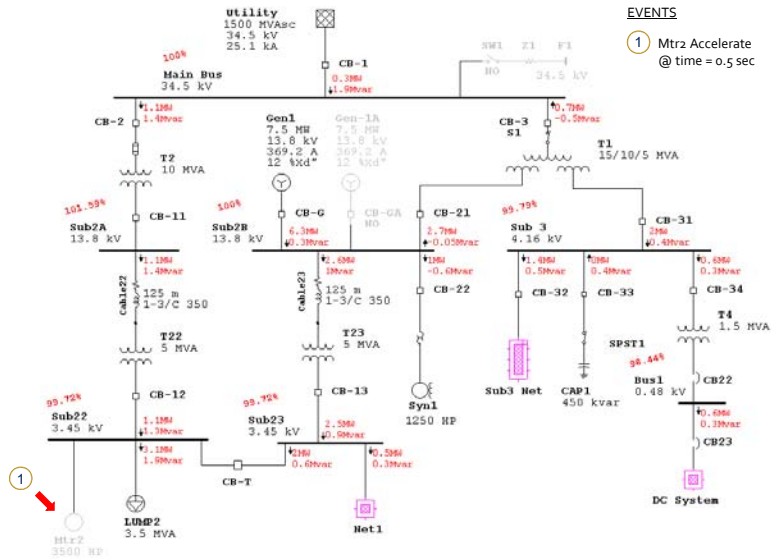


- EVENTS
- CB-T Open
 - ① CB-12 Open @ time = 0.5 sec
 - ② CB-T Close @ time = 0.7 sec

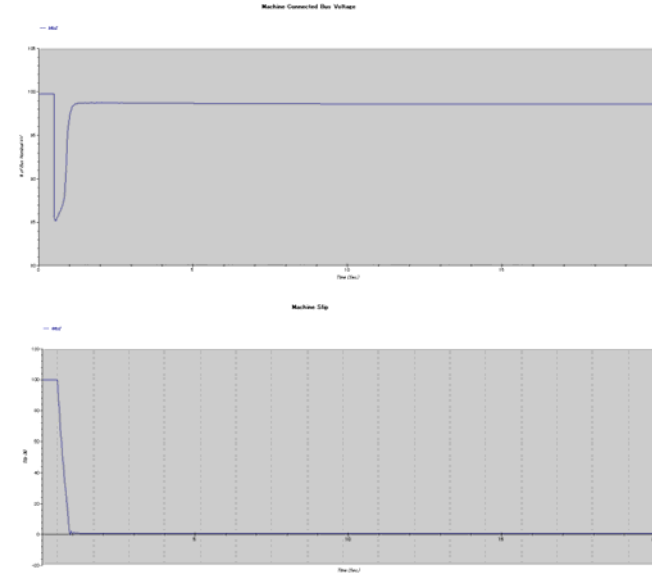
CASE 5 : 系統切換 (2/2)



CASE 6 : 大容量電動機始動 (1/2)



CASE 6 : 大容量電動機始動 (2/2)



アクションの設定 (1/2)

Device Type	Actions	Setting 1	Setting 2
Bus	3 Phase Fault / Clear Fault/	-	-
	LG Fault	-	-
Cable	Fault / Clear Fault	% of total length	-
	Line / Clear Fault	% of total length	-
Line	Fault / Clear Fault	% of total length	-
	Impedance	% of total length	-
Circuit Breaker	Open / Close	-	-
	SPST Switch	-	-
Contactor	Open / Close	-	-
	Fuse	-	-
Generator	Ref. Machine	-	-
	Drop	-	-
	Isch	-	-
	Start	-	-
	Loss Excitation	-	-
	Generation Impact	% change in electrical power	-
	Generation Ramp	% change in electrical power	Time (sec) for % change
	Voltage Impact	% change in reference voltage	-
	Voltage Ramp	% change in reference voltage	Time (sec) for % change
	Delete	-	-
Utility	Ref. Machine	-	-
	Voltage Impact	% change in reference voltage	-
	Voltage Ramp	% change in reference voltage	Time (sec) for % change
	Delete	-	-

アクションの設定 (2/2)

Syn. Motor	Accel	-	-
	Load Impact	% change in loading	-
	Load Ramp	% change in loading	Time (sec) for % change
Ind. Motor	Delete	-	-
	Accel	-	-
	Load Impact	% change in loading	-
Lumped Load	Load Ramp	% change in loading	Time (sec) for % change
	Delete	-	-
	Load Impact	% change in loading	-
MOV	Delete	-	-
	Start	-	-
	U-D Wind Disturbance	-	-
Wind Turbine	Wind Gust	-	-
	Wind Ramp	-	-
	U-D Wind Disturbance	-	-
Wind Turbine (Zone)	Wind Gust	-	-
	Wind Ramp	-	-
	Load Flow (no action, print load flow at the event time)	-	-