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Advanced Power System Planning and Control, and Power System Operation

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Part I

Generation Expansion Planning

IEEE PES GENERAL MEETING TORONTO 2003

Tutorial Course

Modern Heuristic Optimization Techniques with Applications to Power Systems, K. Y. Lee and M. El-Sharkawi (Editors)

Chapter 10 by Kwang Y. Lee

Overview

- Introduction
- Generation Expansion Planning
- Least-Cost GEP Problem
- Improved GA
- Case Studies
- Conclusions

Introduction

- Power System Planning:
  - generation expansion planning, reactive power planning
  - transmission planning, distribution planning
- Planning Problems:
  - nonlinear dynamic optimization problems
  - solved by complete enumeration, which is impossible for a realistic planning problem
- Genetic Algorithm:
  - heuristic optimization method
  - economic dispatch, unit commitment
  - reactive power planning, generation expansion planning
  - power plant control

Generation Expansion Planning

- Least-cost Generation Expansion Planning Problem
  - determine the minimum-cost capacity addition plan that meets the demand and reliability criterion
  - highly constrained nonlinear discrete dynamic optimization problem
- Conventional Approaches for Least-cost GEP
  - LP Approaches: Approximation
  - NLP Approaches - Pontryagin's maximum principle: Local optimal trap
  - DP Approaches: Curse of dimensionality

Generation Expansion Planning

- Commercial Packages such as WASP, EGEAS
  - a DP based on heuristic tunneling technique to find local solutions
- Present Status for GEP Optimization
  - Recent approaches
    - fuzzy set theories
    - artificial intelligent approaches
  - Need an efficient method that can overcome a local optimal trap and the dimensionality problem simultaneously

Generation Expansion Planning

- Advantages of GA-based approaches for least-cost GEP
  - Treatment of discrete variables
  - Overcome the dimensionality problem
  - Possibility to overcome local optimal trap
- Improved Genetic Algorithm (IGA)
  - artificial creation scheme for an initial population
  - stochastic crossover strategy

Least-Cost GEP Problem

- Objective Function J
  - Minimization of discounted investment costs, operating costs, and salvage values:

$$\underset{U_1,\ldots,U_T}{Min} \sum_{t=1}^{T} \{f_t^1(U_t) + f_t^2(X_t) - f_t^3(U_t)\}$$

Least-Cost GEP Problem

- Constraints
  - State Equation

$$s.t. \quad X_t = X_{t-1} + U_t \quad (t = 1, \cdots, T)$$

  - LOLP constraint

$$LOLP\,(X_t) < \varepsilon \qquad (t = 1, \cdots, T)$$

  - Reserve Margin constraint

$$\underline{R} \le R(X_t) \le \overline{R} \qquad (t = 1, \cdots, T)$$

  - Fuel Mix constraint

$$\underline{M_t^j} \le \sum_{i \in \Omega_j} x_t^i \le \overline{M_t^j} \quad (t = 1, \cdots, T \; and \; j = 1, \cdots, J)$$

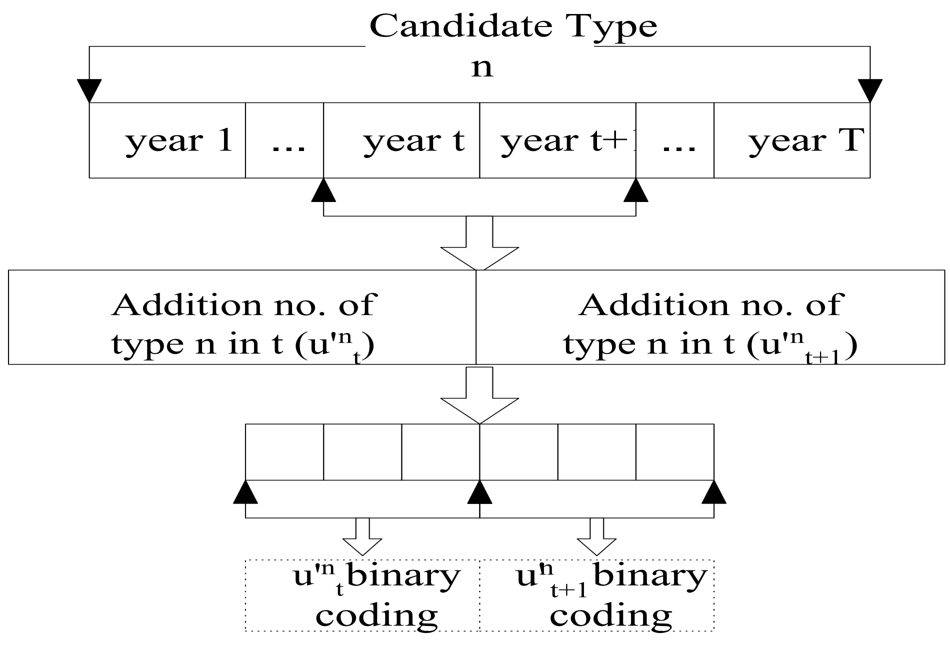
  - Construction Limits

$$0 \le U_t \le \overline{U_t} \qquad (t = 1, \cdots, T)$$

Improved Genetic Algorithm

- Encoding Structure
  - Integer value of added power plants in each year

$$\hat{U}' = \left(u_1'^1, u_2'^1, .., u_T'^1, \cdots, u_1'^n, u_2'^n, .., u_T'^n, \cdots, u_1'^N, u_2'^N, .., u_T'^N\right)^T = \left(\hat{U}'^1, ..., \hat{U}'^n, ..., \hat{U}'^N\right)^T$$

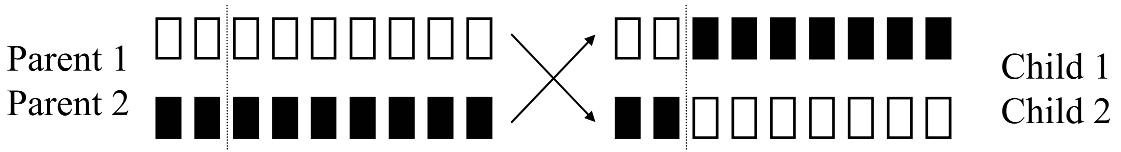


Improved Genetic Algorithm

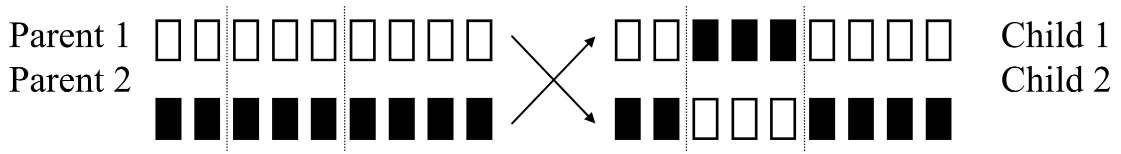
- Creation of an Artificial Initial Population
  - ☞ Objective : create an initial population of strings spread out throughout the whole solution space
  - ☞ Characteristics : Random Generation + Artificial Generation

Improved Genetic Algorithm

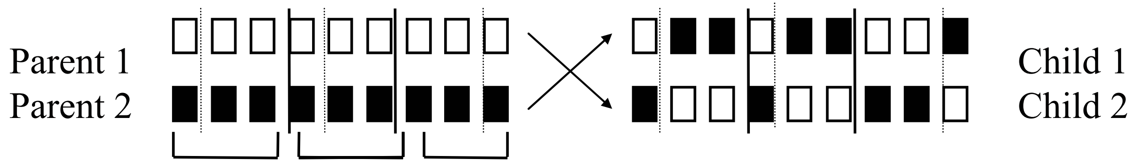
- Stochastic Crossover, Elitism, & Mutation
  - Stochastic Crossover : Random Selection of a Crossover Method among 3 Techniques



1-point crossover

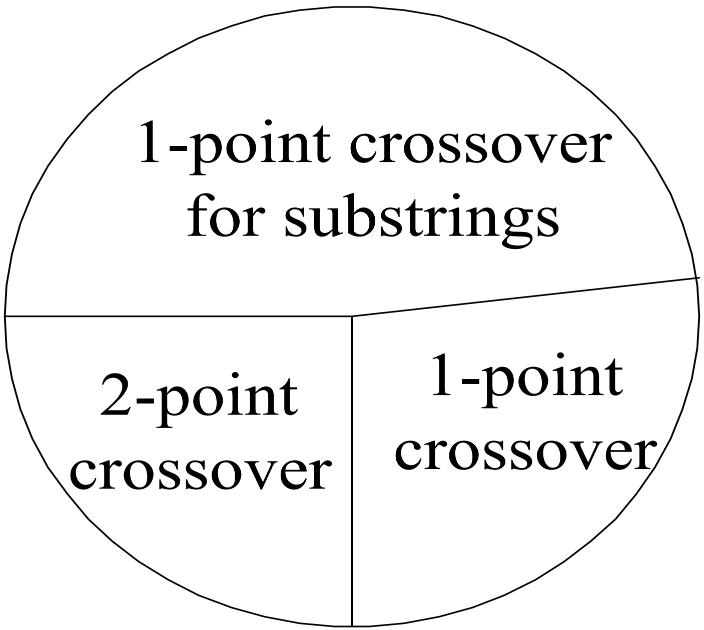


2-point crossover



Improved Genetic Algorithm

- Stochastic Crossover



Case Studies

- Solution Methods
  - IGA
  - SGA
  - Full dynamic programming (DP)
  - Tunnel-constrained DP (TCDP) employed in WASP
- Test Systems
  - Case 1: 15 existing plants, 5 types of candidate plants, 14-year planning horizon
  - Case 2: 24-year planning horizon

Case Studies

- Forecasted Peak Demand
  - 1 stage: 2 years

Stage (Year)	0 (1996)	1 (1998)	2 (2000)	3 (2002)	4 (2004)	5 (2006)	6 (2008)
Peak (MW)	5000	7000	9000	10000	12000	13000	14000
Stage (Year)	-	7 (2010)	8 (2012)	9 (2014)	10 (2016)	11 (2018)	12 (2020)
Peak (MW)	-	15000	17000	18000	20000	22000	24000

Case Studies

- Technical and Economic Data of Existing System

Name (Fuel Type)	No. of Units	Unit Capacity (MW)	FOR (%)	Operating Cost ($/kWh)	Fixed O&M Cost ($/kW-Mon)
Oil #1 (Heavy Oil)	1	200	7.0	0.024	2.25
Oil #2 (Heavy Oil)	1	200	6.8	0.027	2.25
Oil #3 (Heavy Oil)	1	150	6.0	0.030	2.13
LNG G/T #1 (LNG)	3	50	3.0	0.043	4.52
LNG C/C #1 (LNG)	1	400	10.0	0.038	1.63
LNG C/C #2 (LNG)	1	400	10.0	0.040	1.63
LNG C/C #3 (LNG)	1	450	11.0	0.035	2.00
Coal #1 (Anthracite)	2	250	15.0	0.023	6.65
Coal #2 (Bituminous)	1	500	9.0	0.019	2.81
Coal #3 (Bituminous)	1	500	8.5	0.015	2.81
Nuclear #1 (PWR)	1	1,000	9.0	0.005	4.94
Nuclear #2 (PWR)	1	1,000	8.8	0.005	4.63

Case Studies

- Technical and Economic Data of Candidate Plants

Candidate Type	Const-ruction Upper Limit	Capa-city (MW)	FOR (%)	Operating Cost ($/kWh)	Fixed O&M Cost	Capital Cost ($/kW)	Life Time (yrs)
Oil	5	200	7.0	0.021	2.20	812.5	25
LNG C/C	4	450	10.0	0.035	0.90	500.0	20
Coal (Bitum.)	3	500	9.5	0.014	2.75	1062.5	25
Nuc. (PWR)	3	1,000	9.0	0.004	4.60	1625.0	25
Nuc.(PHWR)	3	700	7.0	0.003	5.50	1750.0	25

Case Studies

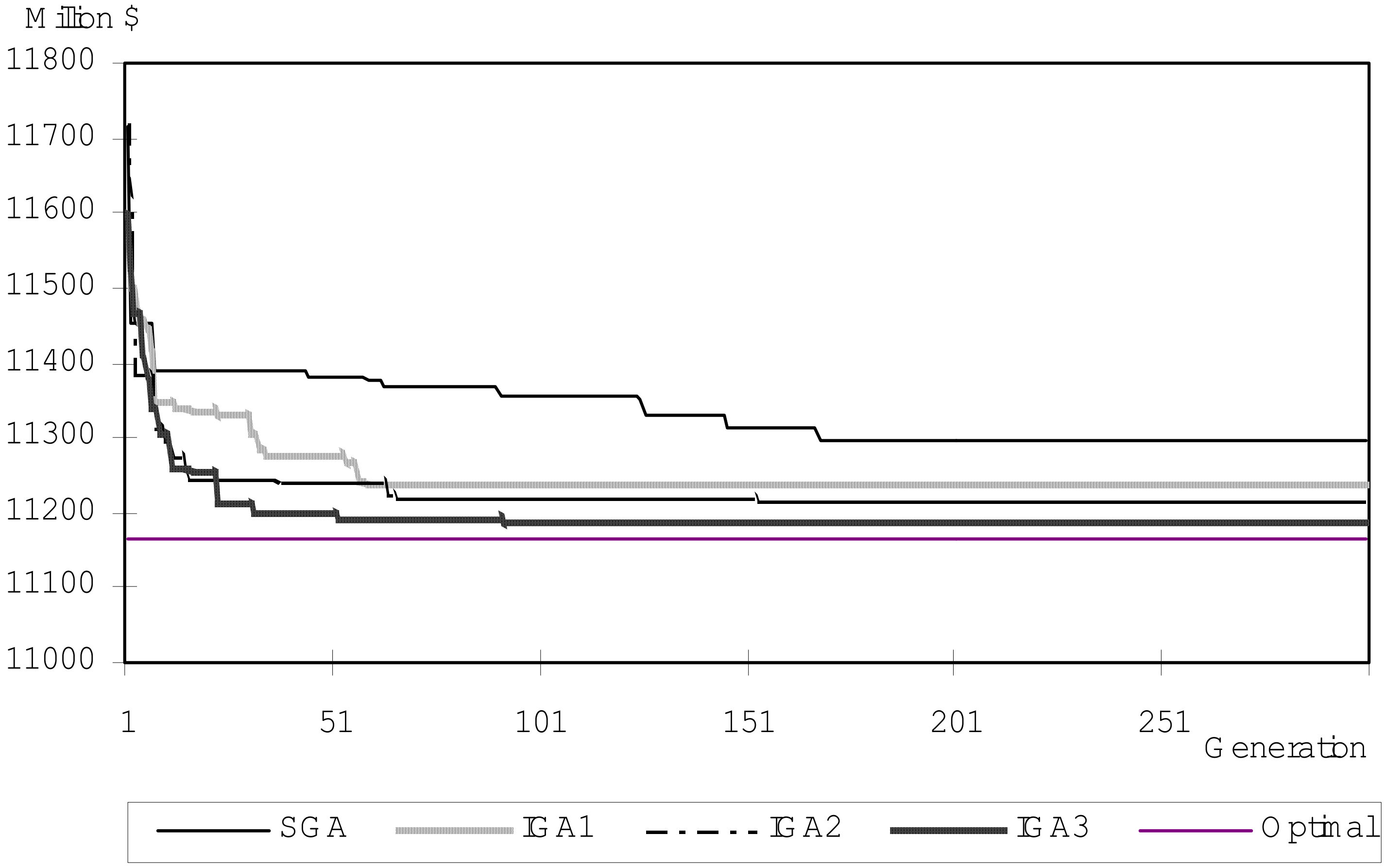
- Parameters for IGA Implementation

Parameters	Value
Population Size	300
Maximum Generation	300
Probabilities of Crossover and Mutation	0.6, 0.01
Number of Elite Strings	3 (1%)
Weights of 1-point, 2-point, and 1-point substring	0.15:0.15:0.70

◆ weights for stochastic crossover techniques are determined empirically with a 6-year planning horizon

Case Studies

- Convergence Characteristics of GA Methods



Case Studies

- Performance Comparison
  - SGA < IGA1 (AIP) < IGA2 (Stochastic Crossover) < IGA3 (AIP + Stochastic Crossover)
    - IGA1, IGA2, IGA3 : Modified Fitness Function + Elitism
- Comparison of best solutions by each method

Solution Method		Cumulative Discounted Cost (10^6 \$)	
		Case 1 (14-year Study Period)	Case 2 (24-year Study Period)
DP		11164.2	unknown
TCDP		11207.7	16746.7
SGA		11310.5	16765.9
IGA	IGA1	11238.3	16759.2
	IGA2	11214.1	16739.2
	IGA3	11184.2	16644.7

Case Studies

- Cumulative Number of New Plants

Type / Year	Oil (200MW)	LNG C/C (450MW)	Coal (500MW)	PWR (1000MW)	PHWR (700MW)
1998	3 (5)[1]	2 (1)	2 (3)	0 (1)	2 (0)
2000	5 (6)	3 (1)	5 (6)	0 (1)	4 (1)
2002	5 (7)	3 (1)	5 (6)	0 (2)	4 (1)
2004	8 (10)	7 (3)	6 (7)	0 (2)	4 (1)
2006	10 (12)	10 (3)	6 (7)	0 (2)	6 (2)
2008	10 (13)	10 (3)	6 (9)	0 (2)	6 (2)
2010	10 (13)	10 (3)	6 (9)	0 (2)	6 (4)
2012	14	11	8	1	7
2014	17	14	8	1	7
2016	19	15	10	1	9
2018	19	17	10	3	9
2020	20	18	12	3	9

1. The figures within parenthesis denote the results of IGA3 in Case 1.

Case Studies

- Computation Time

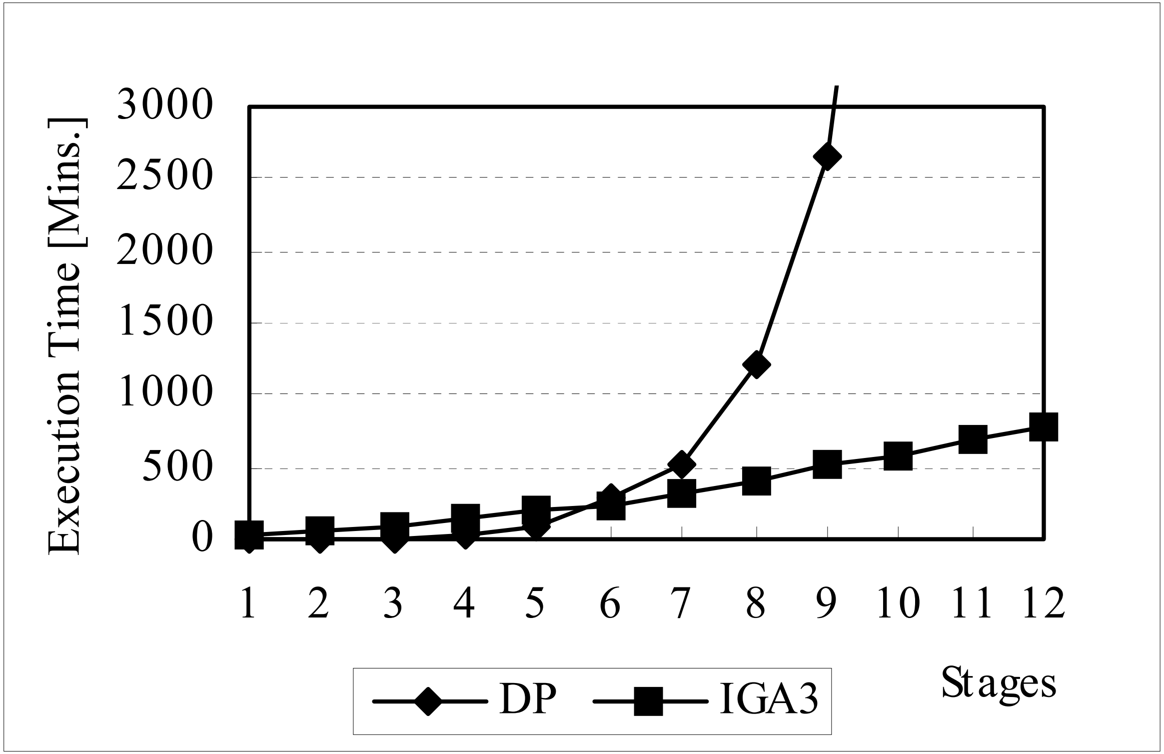


Fig. 5. Observed execution time for the number of stages

Conclusions

- Development of an Improved Genetic Algorithm and Its Application to Least-cost GEP
  - AIP
  - Stochastic Crossover
  - Modified Fitness Function
  - Elitism
- Better Solutions by IGA than SGA, TCDP of WASP
- Application to Practical Large-scale GEP and Reactive Power Planning Problems

Part II

Network Planning

IEEE PES GENERAL MEETING TORONTO 2003

Tutorial Course

Modern Heuristic Optimization Techniques with Applications to Power Systems, K. Y. Lee and M. El-Sharkawi (Editors)

Chapter 11 by Alcir Monticelli, Rubén Romero, and Eduardo Asada

Outline

- Three algorithms for network planning are presented: simulated annealing, genetic algorithm and tabu search.
- Four important power network planning problems.
- Covered problems: operation and expansion planning

Planning Problems

1. Reconfiguration of primary distribution systems
2. Allocation of capacitor in distribution systems
3. Distribution system expansion planning
4. Transmission Network Expansion Planning

Reconfiguration of Distribution Feeders

Consists in finding the optimal configuration of distribution feeders in the topology of a radial system, with part of the feeder sections in operation while others remain de-energized.

Reconfiguration of Distribution Feeders Mathematical Model

- Mixed integer non-linear program (MINLP)
- The problem: complexity increases in exponential form according to the number of interconnected branches

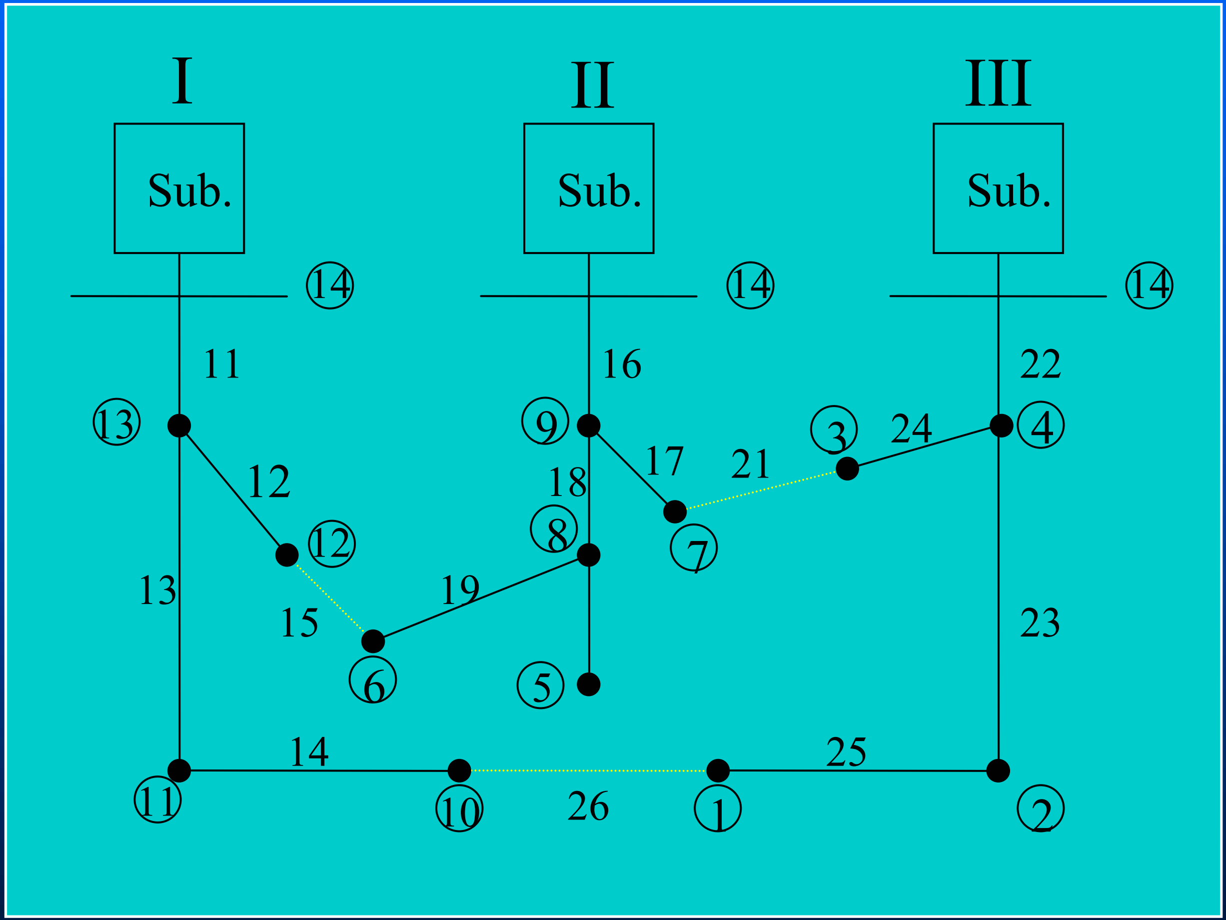
Reconfiguration of Distribution Feeders Mathematical Model (2)

- The problem is state as follows:

  Find the set of trees that lead to the minimization of the objective function, satisfying the voltage drop limits, the capacities of feeder sections and transformers, and power flow equations.

Reconfiguration Problem: Initial Topology

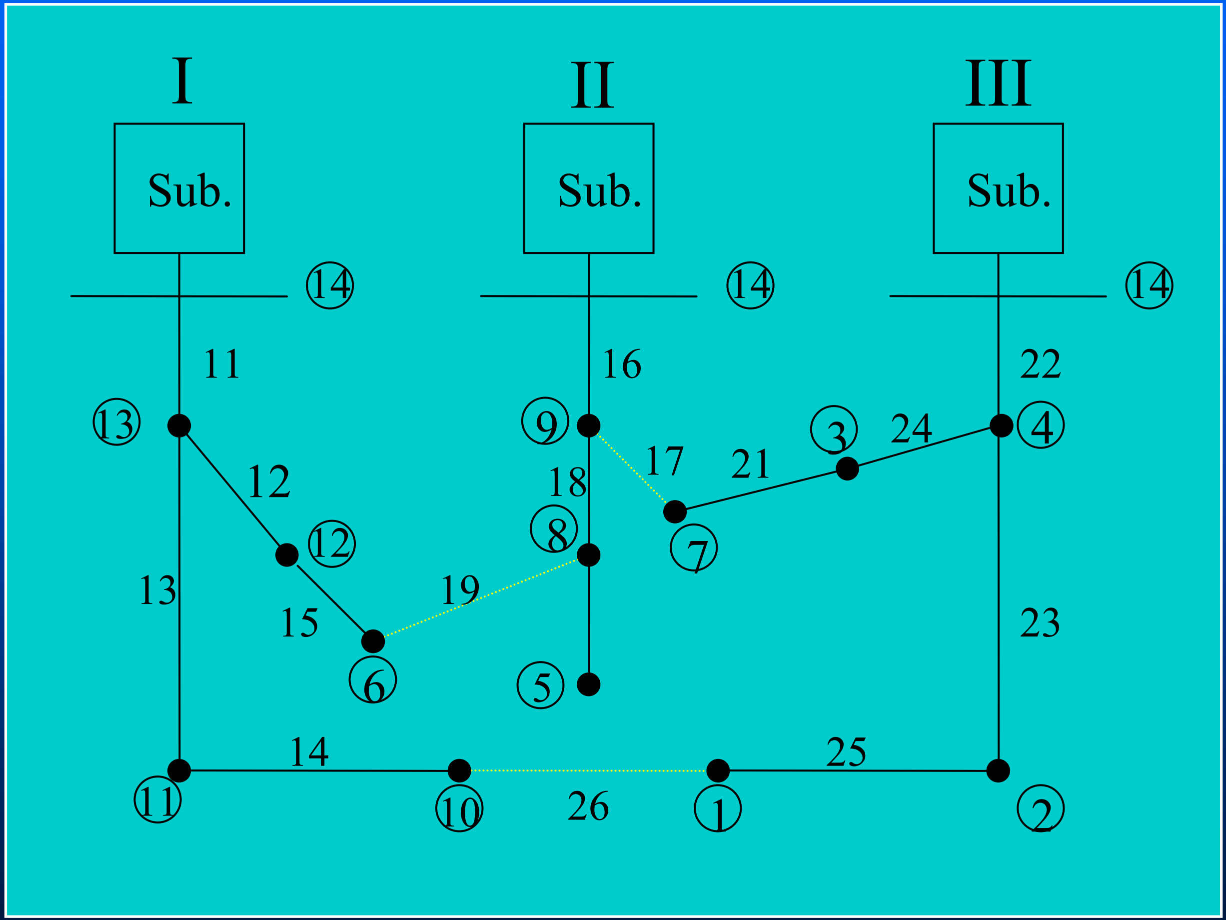
Total Losses
511.4 kW



Reconfiguration Problem: Optimal Topology

Total Losses
466.1 kW

revious Losses
11.4 kW



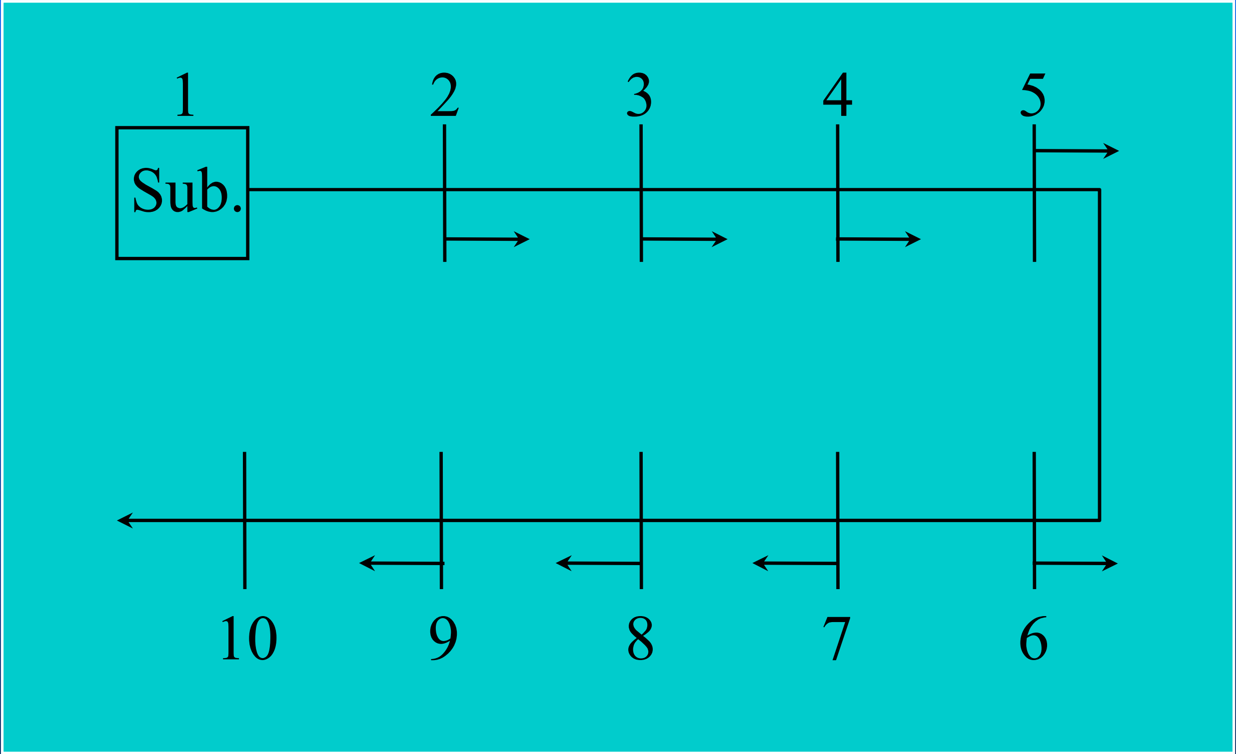
Optimal Capacitor Placement

- Capacitor banks are added to radial distributions systems for power factor correction, loss reduction, voltage profile improvement.
- Optimal capacitor placement aims to determine capacitor types, sizes, locations and control schemes.

Optimal Capacitor Placement Mathematical Model

- Mixed integer nonlinear program
- The objective function is non-differentiable
- Hard large-scale combinatorial problem
- The objective function is commonly formulated as the cost of losses and investments over a period of time.
- Two types of capacitor: Fixed capacitor and switched capacitors

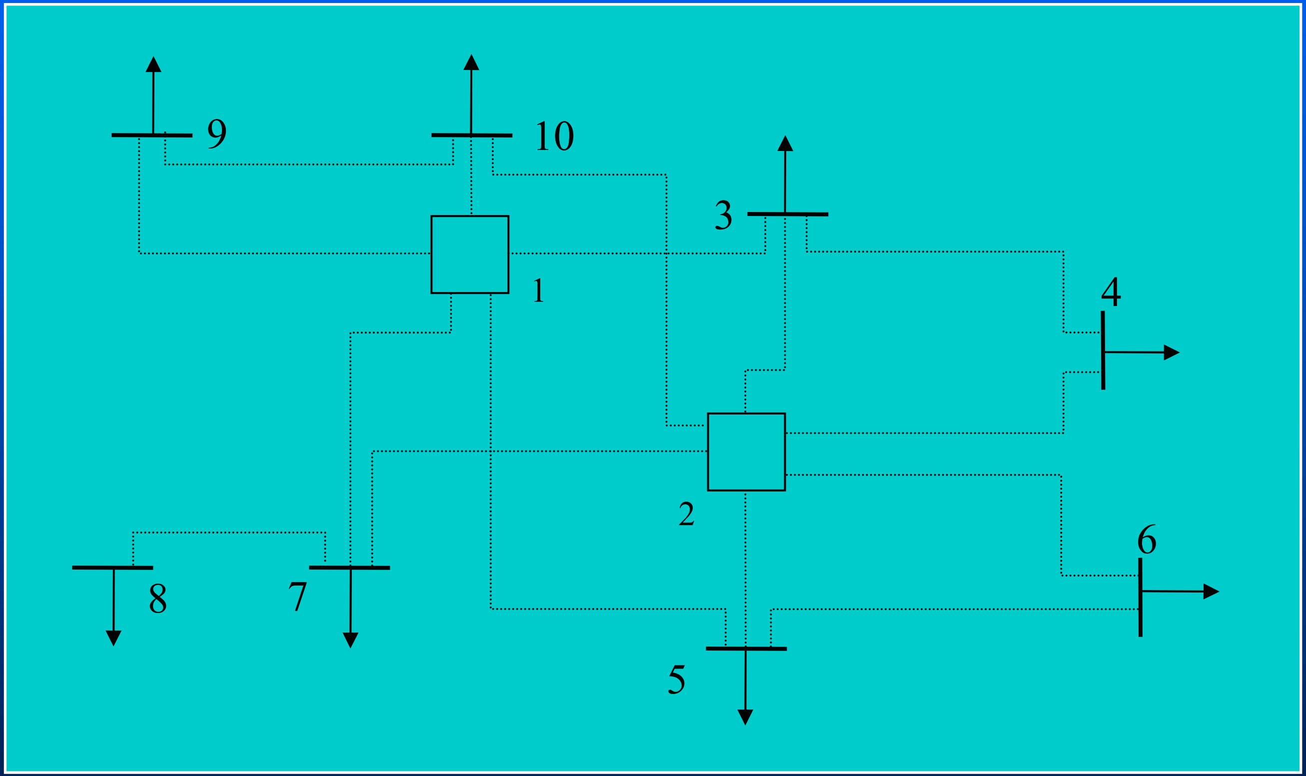
Example of a Radial Distribution System



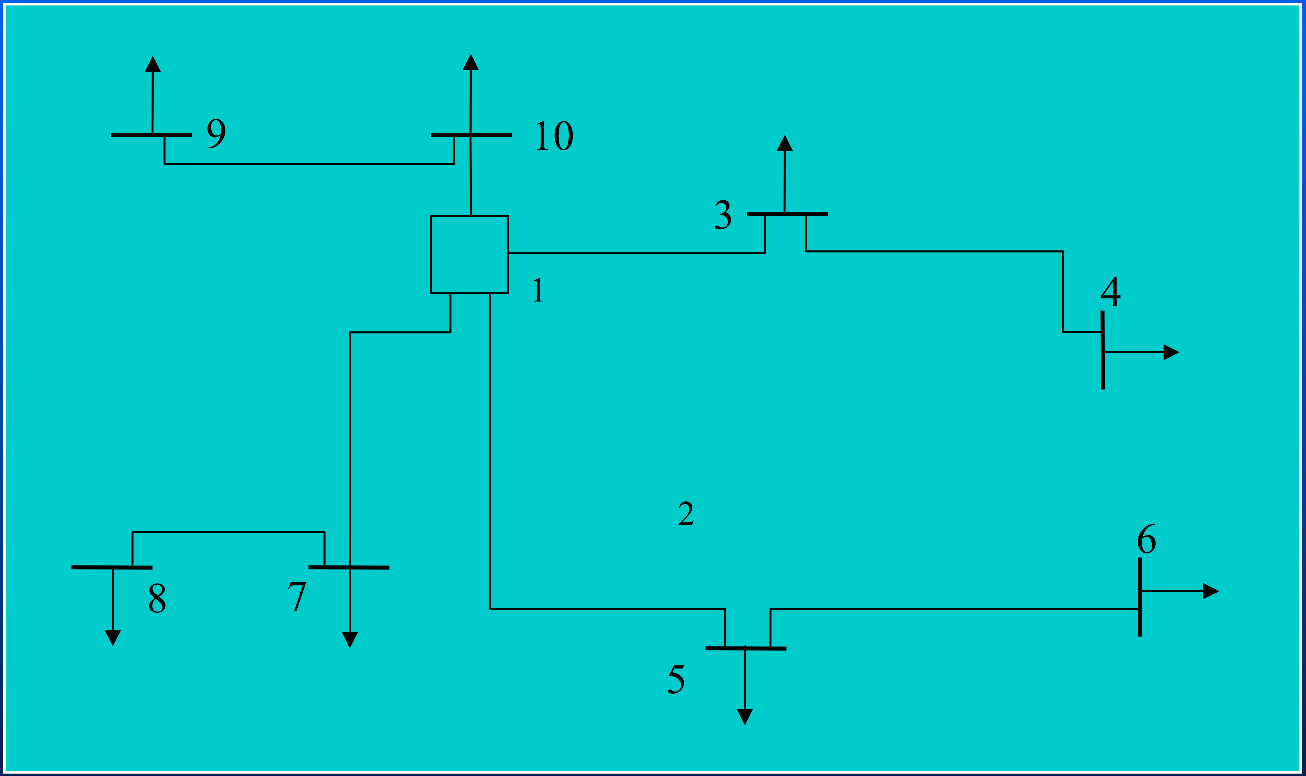
Distribution System Expansion Planning

- Addition of new substations and primary feeders to distributions systems to cope with demand growth as well as geographical expansion.
- Special case – *Green field* planning
- Radiality constraint

Distribution System Expansion Problem Initial Configuration



Optimal Solution



Transmission Network Expansion Planning

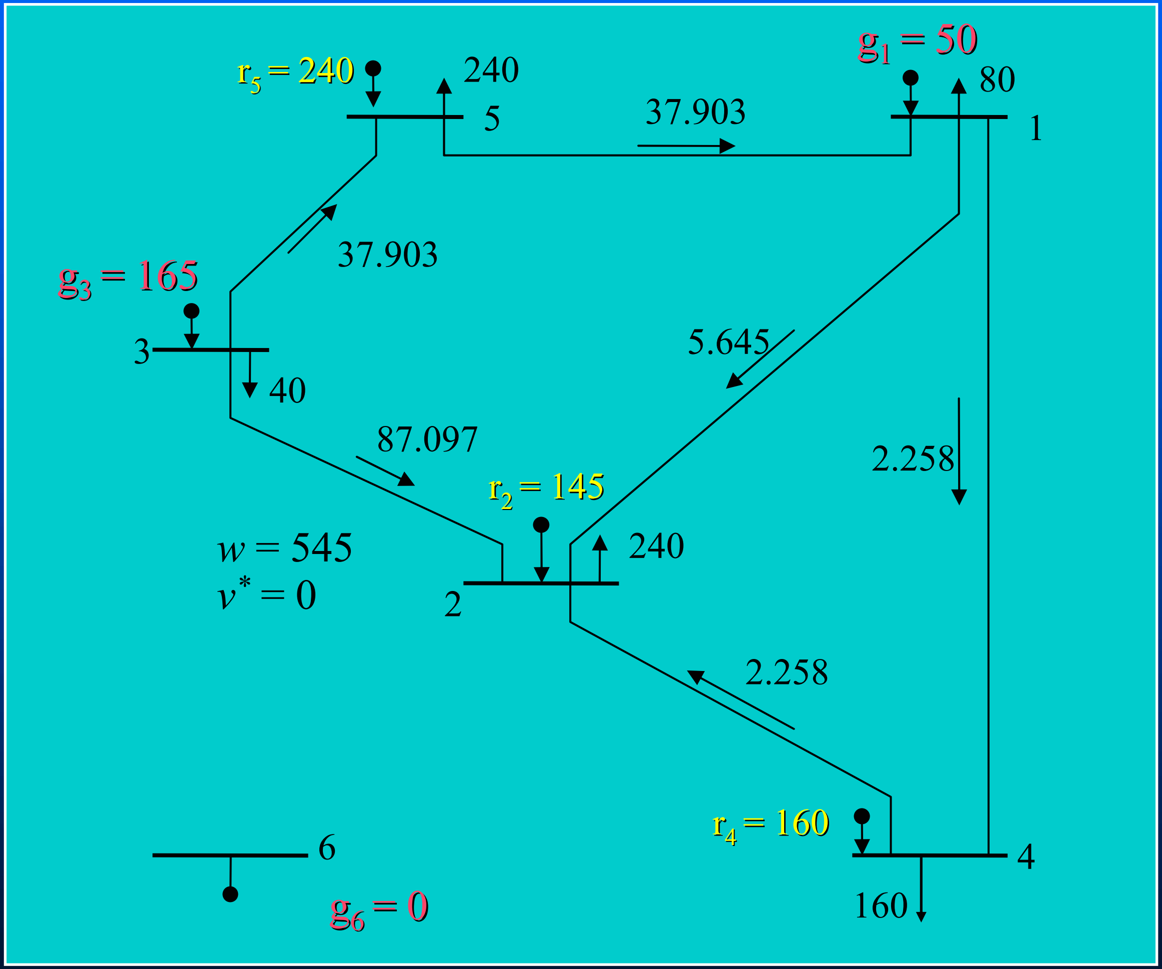
- Static expansion problem
  – Planning is made in one stage

- Dynamic expansion problem
  – Planning is made in various stages

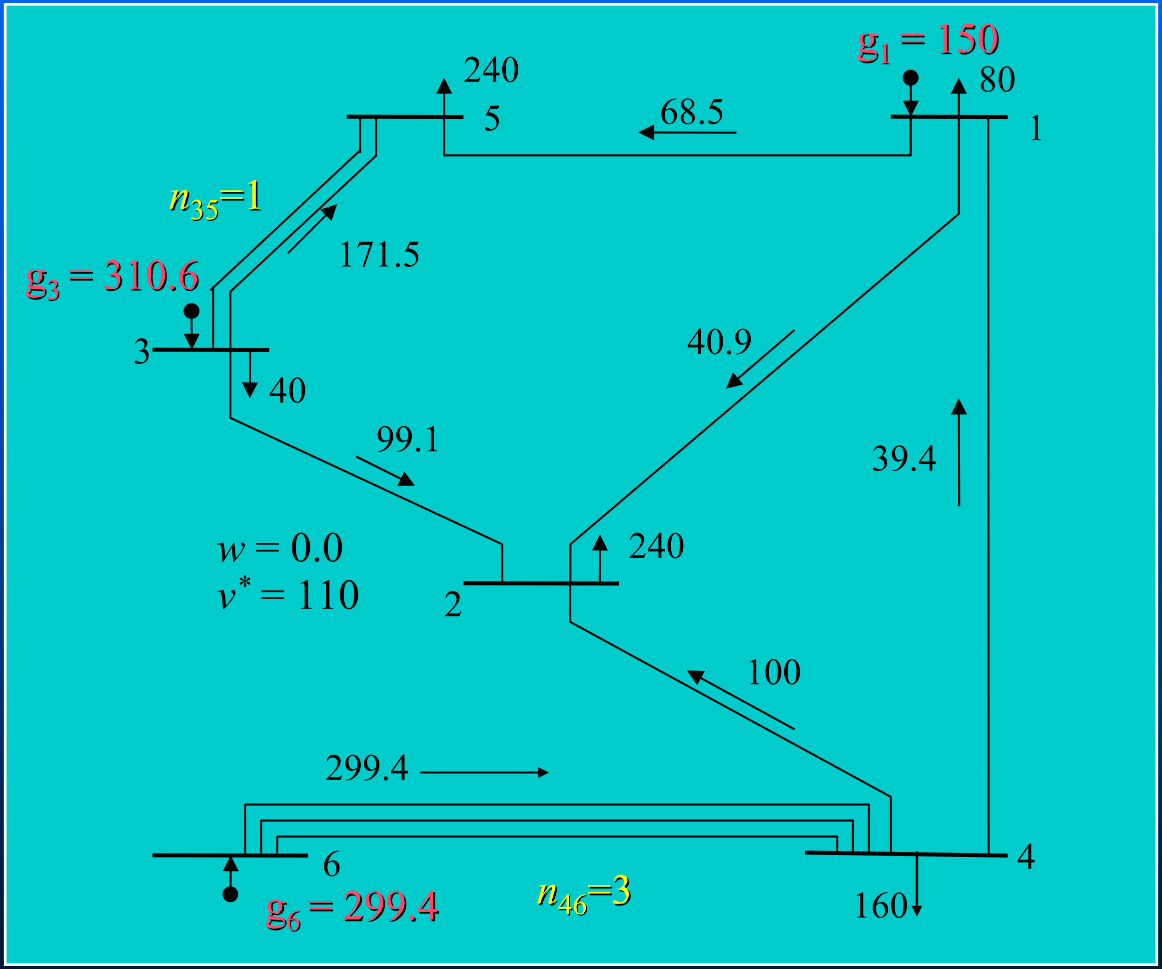
Transmission Network Expansion Problem Mathematical Model

- Static model
- Mixed integer non-linear programming problem
- Power network is represented by a DC power flow model

Network Planning: Initial Topology



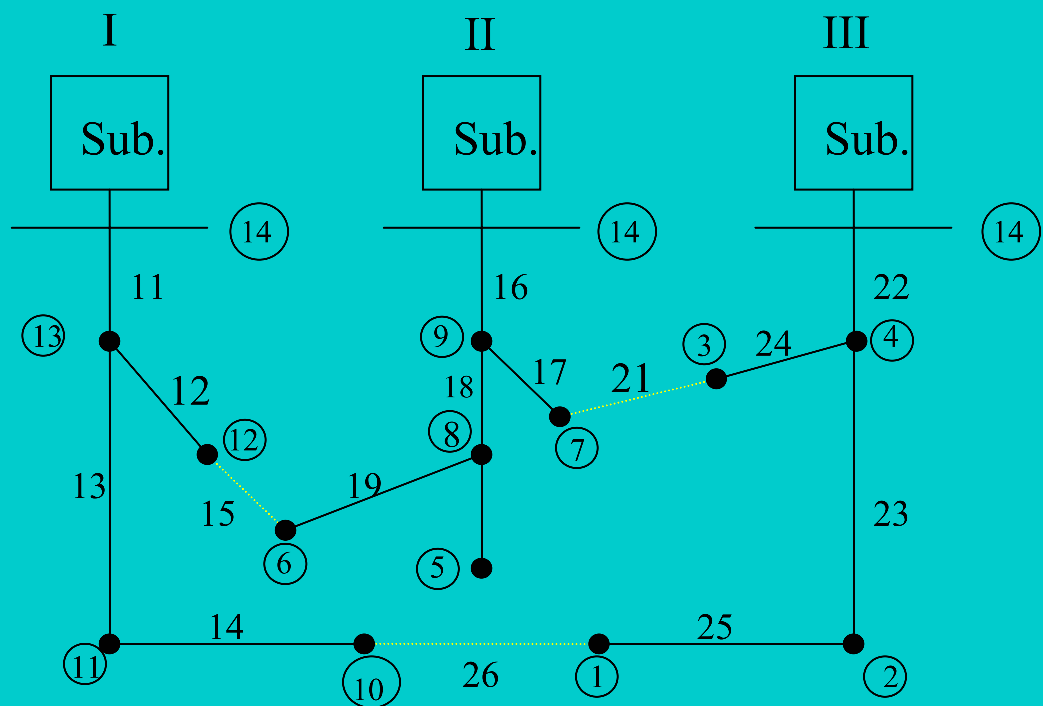
Optimal Solution with Rescheduling



Coding and Neighborhood Structure

1. Reconfiguration of distribution feeders
2. Optimal capacitor placement
3. Distribution system expansion planning
4. Transmission network expansion planning

1. Reconfiguration of Distribution Feeders



Feeder section	11	...	15	16	...	20	21	22	23	24	25	26
$p_1=$	1	...	0	1	...	1	0	1	1	1	1	0

Coding and Neighborhood Structure

Feeder section	11	...	15	16	...	20	21	22	23	24	25	26
p_1=	1	...	0	1	...	1	0	1	1	1	1	0

	11	...	16	17	...	22	23	24	25	15	21	26
p_1=	1	...	1	1	...	1	1	1	1	0	0	0

p_1=	11	12	...	16	17	18	19	20	22	23	24	25

Coding and Neighborhood Structure

- A good configuration should make it easier to deal with infeasibilities.
- The coding is connected to the employed coding.
- Considering the first coding, a simple neighborhood is obtained by swapping a de-energized feeder with an energized one.

2. Optimal Capacitor Placement

- The capacitor placement problem has two types of variables: discrete and continuous
- Codings
  - Fixed capacitors

Bus	1	2	3	4	5	6	7	8	9	10
p_1=	0	0	1	0	2	3	0	0	0	0

  - Variable capacitor banks

Bus	1	2	3	...	1	2	3	...	1	2	3	...
p_1=	0	2	3	...	0	2	2	...	0	1	1	...
	Level 1				Level 2				Level 3			

Alternative Coding

- Three vectors, one for each load level.

Bus	1	2	3	4	5	6	7	8	9	10
$p_{1A}=$	0	2	3	0	2	4	0	0	0	0

Bus	1	2	3	4	5	6	7	8	9	10
$p_{1M}=$	0	2	2	0	2	3	0	0	0	0

Bus	1	2	3	4	5	6	7	8	9	10
$p_{1B}=$	0	1	1	0	2	3	0	0	0	0

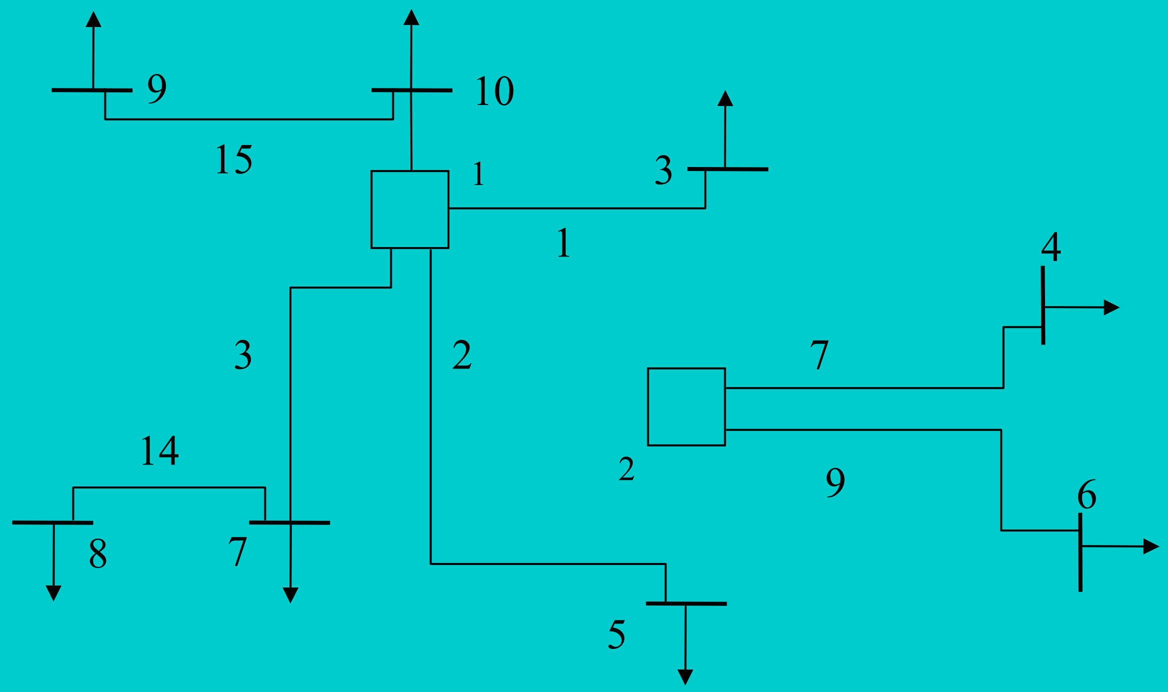
Neighborhood Structure

- Remove a bank from a bus and adding to another bus (swapping)
- Addition of a bank to a bus
- Removal of a previously added bank

Feasibility Conditions

- In the case of variable capacitors, the number of capacitor at each bus for a lower level of the load should be less than the number of capacitors for high load conditions.
- Load and voltage magnitude constraints.
- Keep the feasibility while the algorithm traverses the search space.

3. Distribution System Expansion Planning



Feeder	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$p_1 =$	1	1	1	0	1	0	2	0	2	0	0	0	0	1	1

Coding

Feeder	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$p_1=$	1	1	1	0	1	0	2	0	2	0	0	0	0	1	1

ordered

Feeder	1	2	3	5	14	15	7	9	4	6	8	10	11	12	13
$p_1=$	1	1	1	1	1	1	2	2	0	0	0	0	0	0	0

Separate vectors

$p_{1A}=$	1	2	3	5	14	15

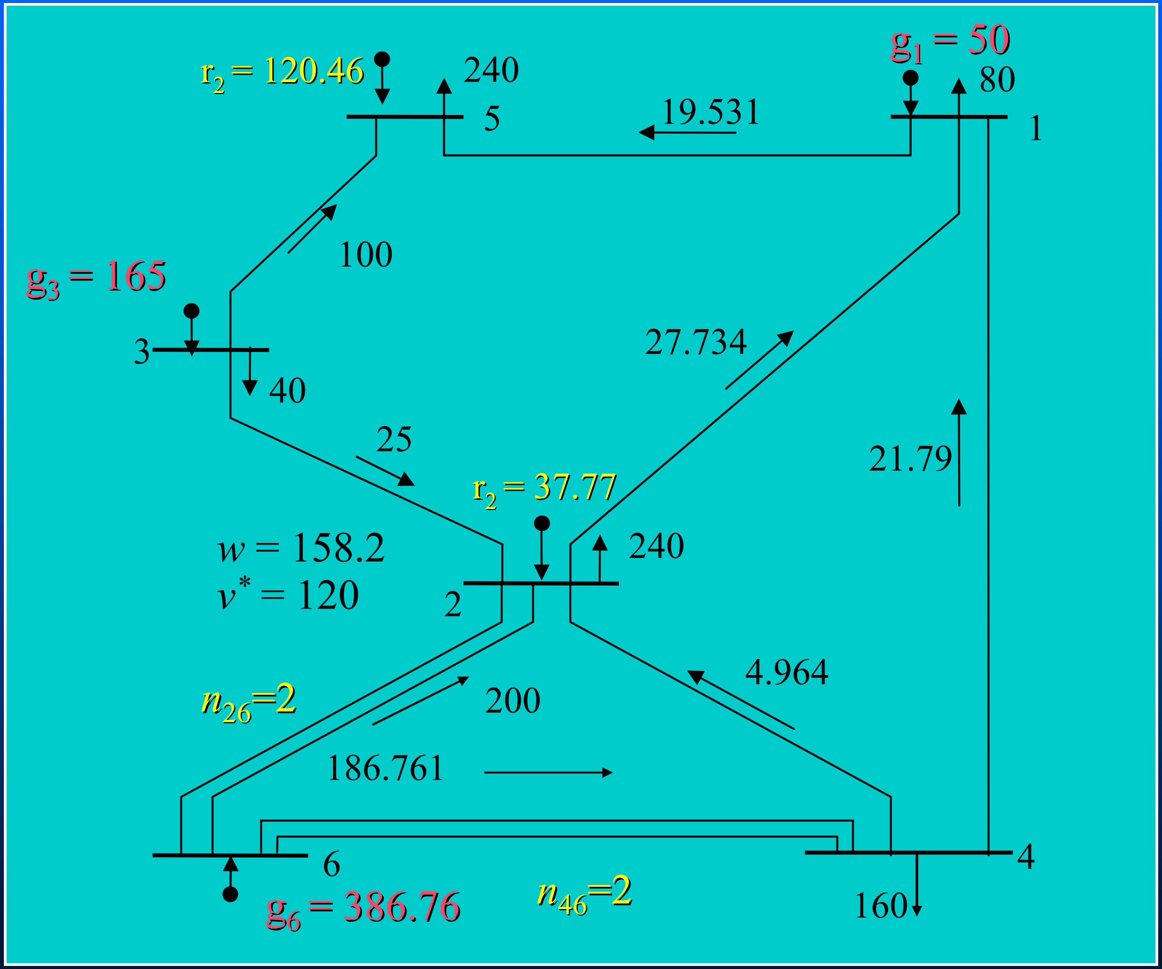
$p_{1B}=$	7	9

$p_{1C}=$	4	6	8	10	11	12	13

Neighborhood Structure

- Remove one feeder and add another one that does not form part of the current configuration.
- Allow infeasible configurations.
- Accept only feasible-to-feasible transitions.
- Accept transitions through infeasible solutions.

4. Transmission Network Expansion Planning



Coding

- Only the integer variables are codified - the number of circuits that can be added in a right-of-way

Circuit	1-2	1-3	1-4	...					2-6					4-6	5-6
$p_1=$	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0

Neighborhood Structure

- Formed by:
  1. Adding new circuit,
  2. Removing a previously added circuit.
  3. Swapping two circuits.
- For networks with a high degree of islanding, the neighborhood structure has to consider the addition of multiples circuits at a time

Neighborhood Structure

- In transmission expansion planning problem it is frequently the case that the entire neighborhood of a given configuration is formed only by infeasible configurations.
- The infeasibilities are penalized in the objective function.

Implementation Details

- Simulated Annealing
- Genetic Algorithm
- Tabu Search

Conclusions

- This part addressed the coding and the neighborhood definitions of four power network problem:
  - optimal reconfiguration of distribution systems
  - capacitor placement in primary distribution feeders
  - optimal distribution system expansion
  - optimal expansion of transmission networks

Part III
A Comprehensive Comparison of FACTS Devices for Enhancing Static Voltage Stability

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Contents

- Introduction
- Static Voltage Stability
- Flexible AC Transmission System (FACTS)
- System and Analysis Tools
- Numerical Results
- Conclusion

Introduction

- Voltage instability has been a major concern in power systems, especially in planning and operation, as there have been several major power interruptions associated with this phenomenon, in recent years.
- Power system network can be modified to alleviate voltage instability or collapse by adding Flexible AC Transmission System (FACTS) devices at the appropriate locations.
- There are various types of FACTS devices available for this purpose, namely,
  - Static Var Compensator (SVC),
  - Static Synchronous Compensator (STATCOM),
  - Thyristor-Controlled Series Capacitor (TCSC),
  - Static Synchronous Series Compensator (SSSC) and
  - Unified Power Flow Controller (UPFC).

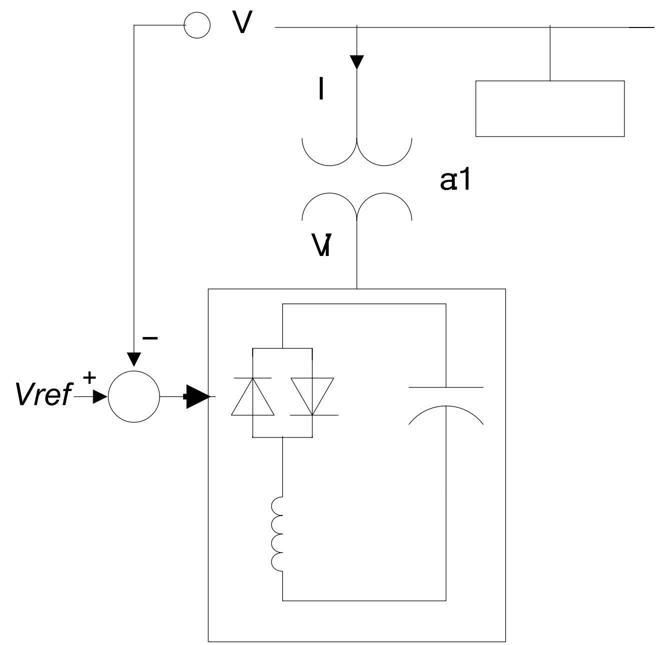
- Each of these FACTS devices, however, has its own characteristics and limitations.
- Optimal placement and sizing of these FACTS devices are important issues for voltage stability improvement.

Static Voltage Stability

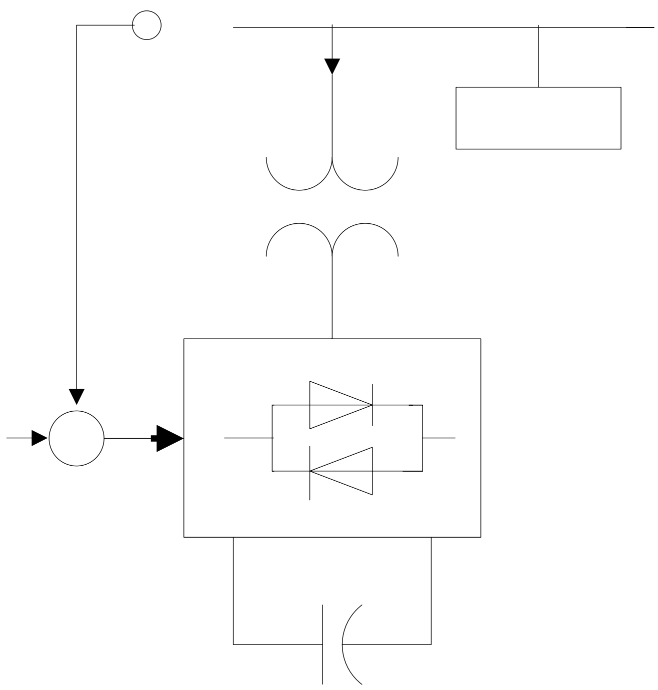
- Static voltage instability is mainly associated with reactive power imbalance.
- Slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage.
- This phenomenon can be seen from the plot of the voltage at receiving end versus the power transferred, which are popularly referred to as P-V curve or "Nose" curve.
- In static voltage stability, Continuation Power Flow (CPF) process are used to investigate static voltage stability.
- Maximum load that can be increased from the base case represents voltage stability margin or loading margin (LM) of the system.

- There are various types of FACTS devices:
  - SVC
  - STATCOM
  - TCSC
  - SSSC
  - UPFC
- They can be connected to a transmission line at any appropriate location in series, in shunt or in a combination of series and shunt.
- SVC and STATCOM are connected in shunt, whereas TCSC and SSSC are connected in series.
- UPFC, on the other hand, is connected in series and shunt combination.

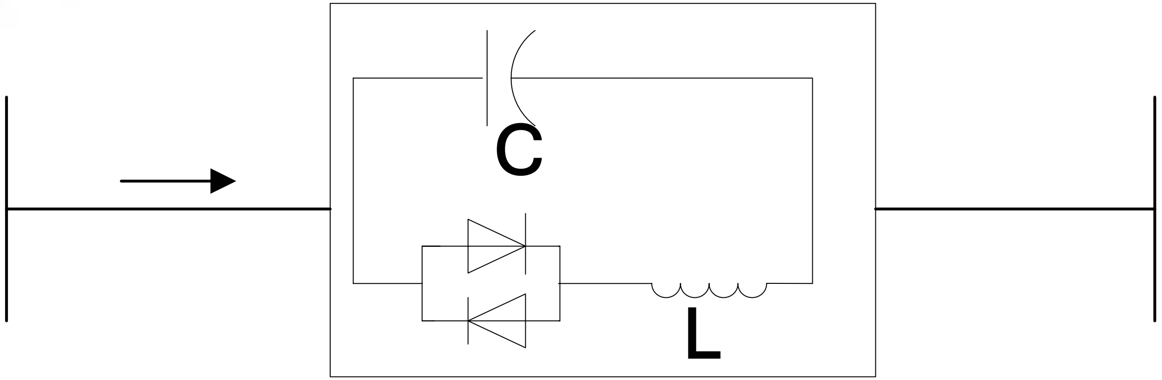
- SVC is a shunt connected static Var generator/load whose output is adjusted to exchange capacitive or inductive current.
- It is composed of a controllable shunt reactor and shunt capacitor(s).
- Total susceptance of SVC can be controlled by controlling the firing angle of thyristors.



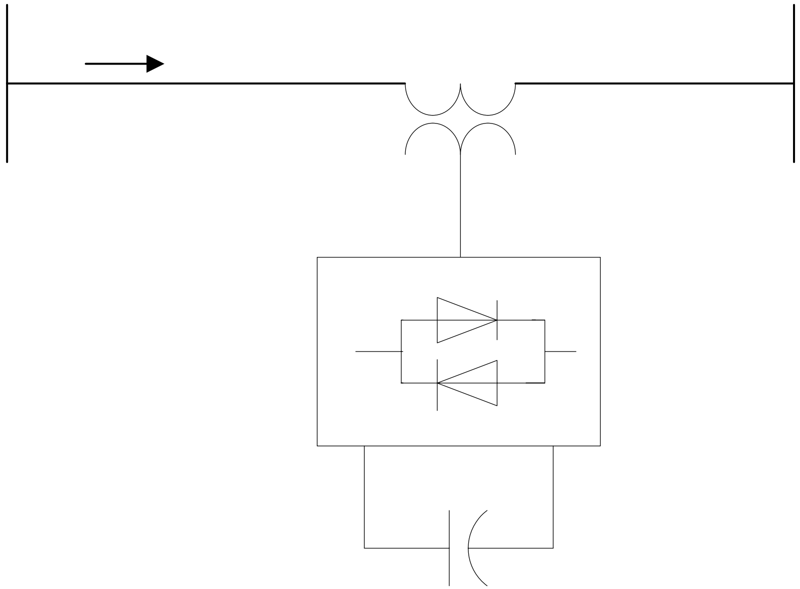
- STATCOM is the voltage-source converter, which converts a DC input voltage into AC output voltage in order to compensate the active and reactive needed by the system.
- STATCOM could be viewed as superior to SVC, as STATCOM provides better terminal characteristics compared to diminishing characteristics at low terminal voltages by SVC.



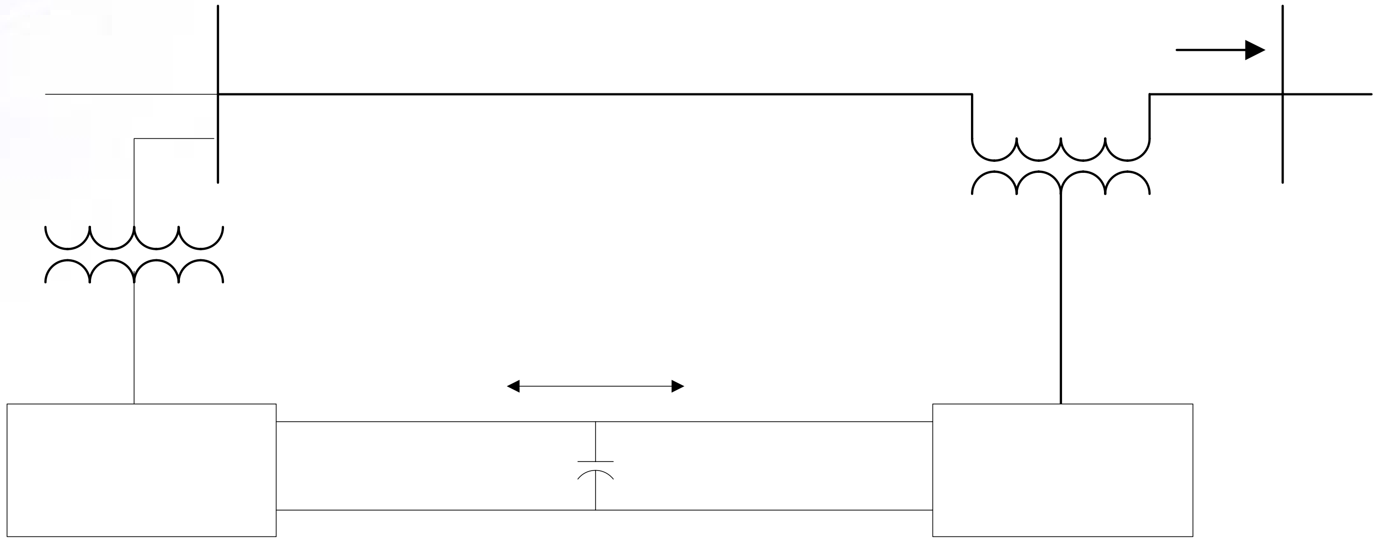
- TCSC is similar to SVC but it is connected in series with the line.
- Its controllers use TCR in parallel with segments of series capacitor bank.
- The total susceptance of the line is controlled by controlling the firing angle of the thyristor.



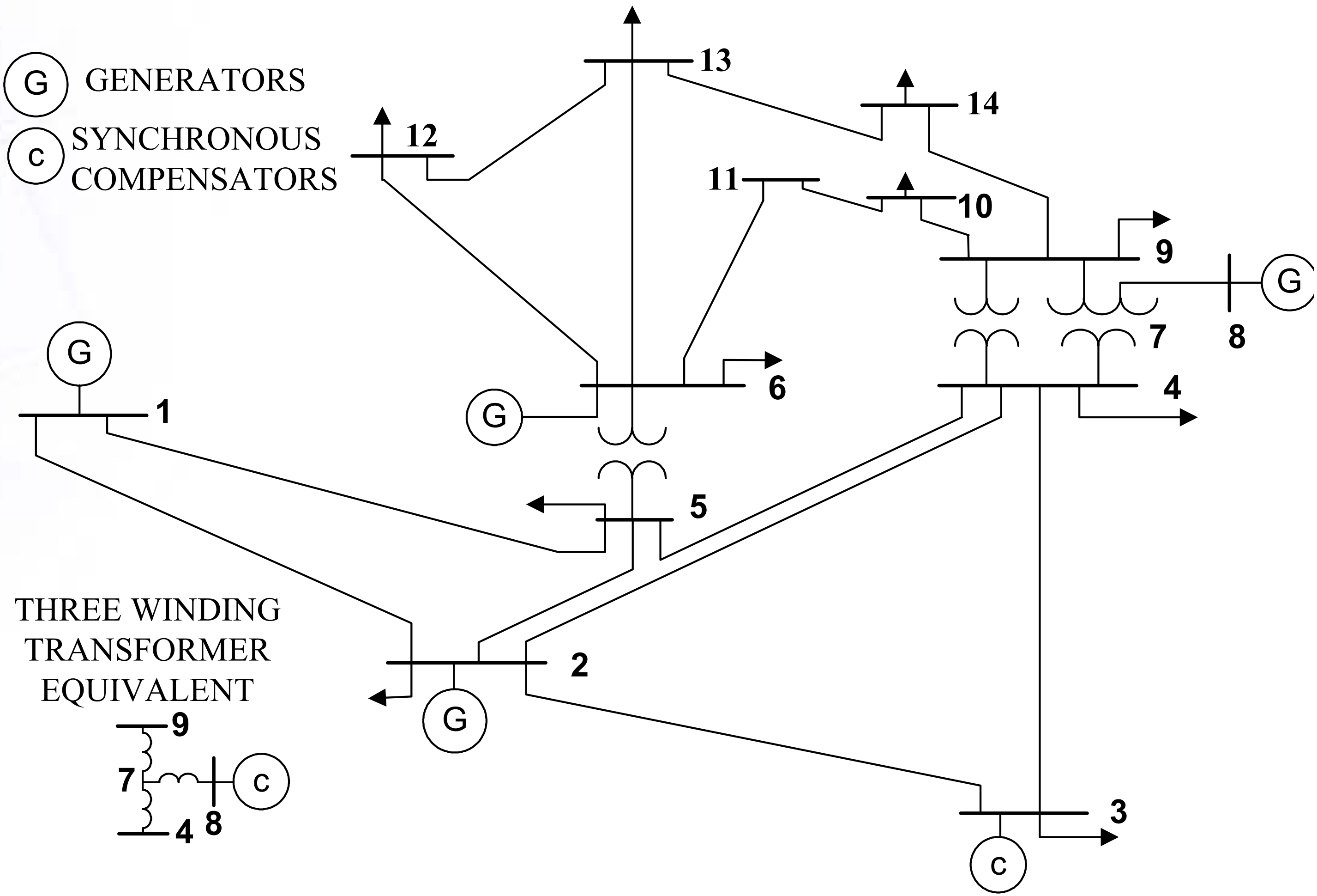
- SSSC is similar to the STATCOM, as it is based on a DC capacitor fed Voltage Source Inverter (VSI) that generates a three-phase voltage at fundamental frequency, but it is connected in series injected through a transformer.



- UPFC consists of two identical VSIs: one in shunt and the other one in series with the line.
- Two inverters, namely shunt inverter and series inverter which operate via a common DC link with a DC storage capacitor, allow UPFC to independently control active and reactive power flows on the line as well as the bus voltage.



- Two test systems, namely the IEEE 14-bus test system and the modified IEEE 14-bus test system, are used in this paper.
- The modification from the original IEEE 14-bus test system is that generators located at buses 6 and 8 were changed from synchronous compensators to generators.
- There are twenty branches and fourteen buses with eleven loads totaling 259 MW and 81.4 Mvar.
- A single line diagram of the modified IEEE 14-bus test system is depicted in the next Figure.

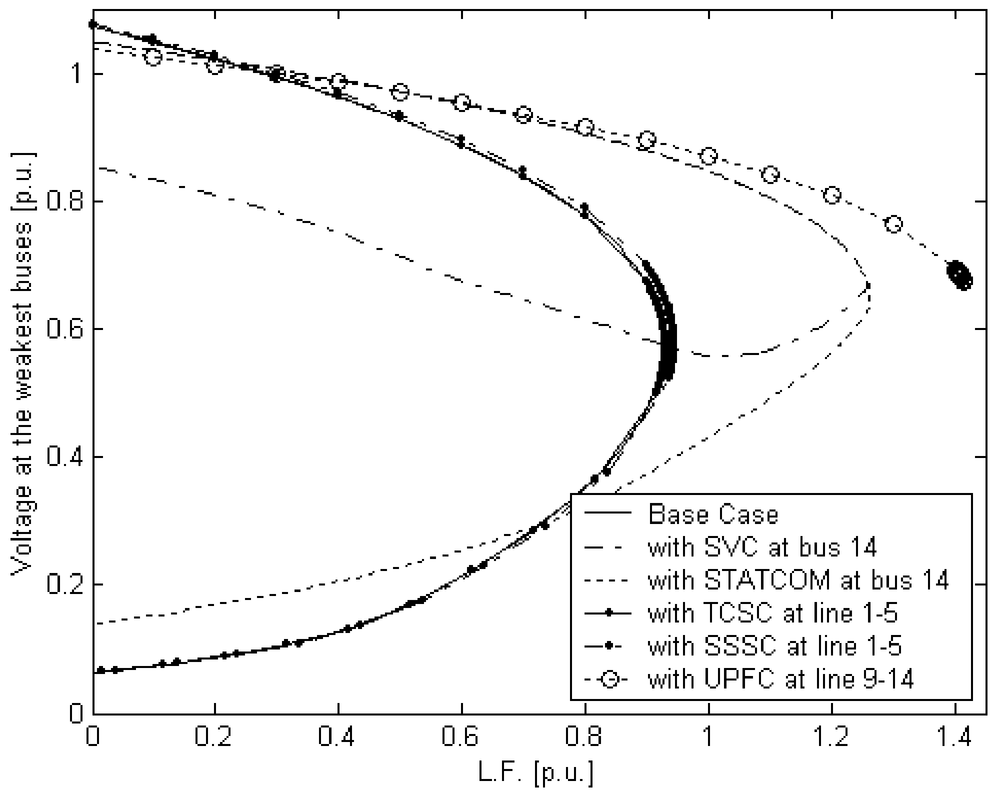

G
GENERATORS
C
SYNCHRONOUS
COMPENSATORS
13
12
14
11
10
9
G
7
8
G
1
G
6
4
5
THREE WINDING
TRANSFORMER
EQUIVALENT
9
7
C
4
8
2
G
3
C

Summary of Capacities of FACTS Devices for the modified IEEE 14-bus test system

Type	Location	Sizing	
		MVAR	MW
SVC	Bus 14	150	
STATCOM	Bus 14	150	
TCSC	Line 1-5	2.4	
SSSC	Line 1-5	12.5	0.2
UPFC	Line 9-14	18.4 (series) / 100 (shunt)	0.45 (series)/ 2.3 (shunt)

PV Curves and Voltage Profiles

- Figure and Table below show PV curves and LM of the base case with FACTS devices for the modified IEEE 14-bus test system.

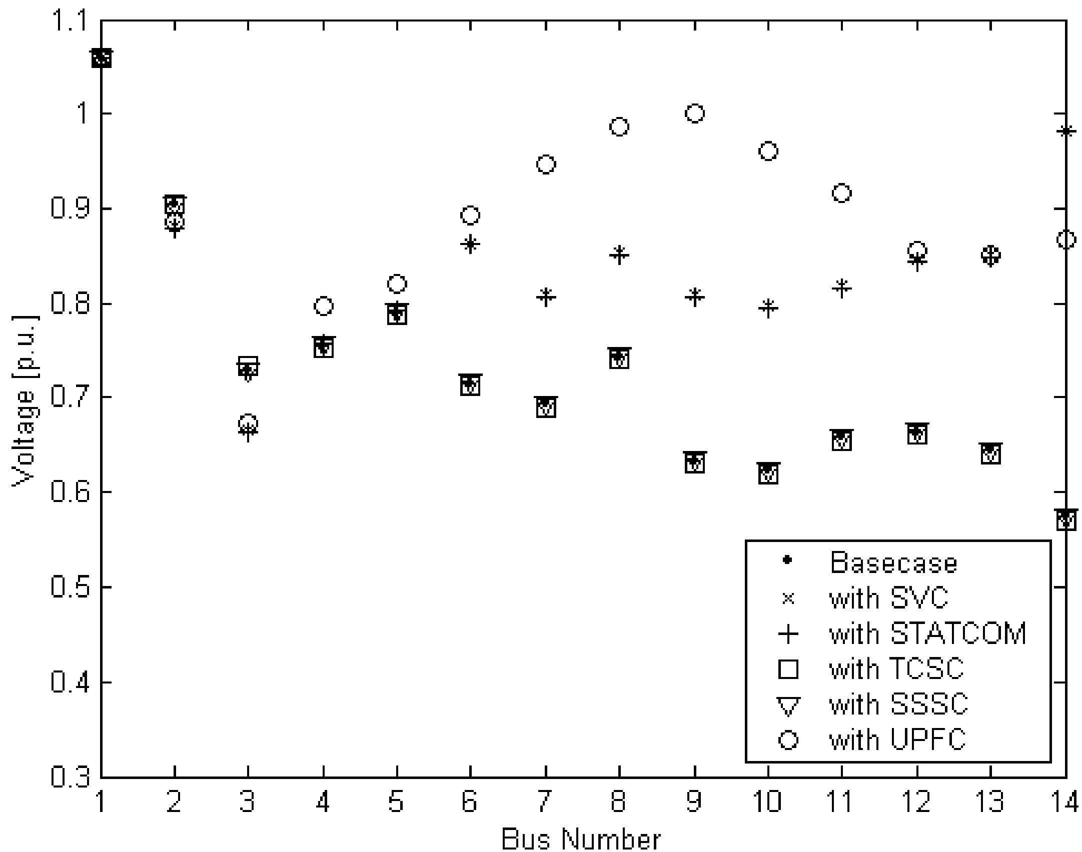


PV Curves and Voltage Profiles

Case	LM [p.u]	% Increase
Base Case	0.9278	-
SVC	1.2606	35.9
STATCOM	1.2625	36.1
TCSC	0.9307	0.3
SSSC	0.9452	1.9
UPFC	1.4165	52.7

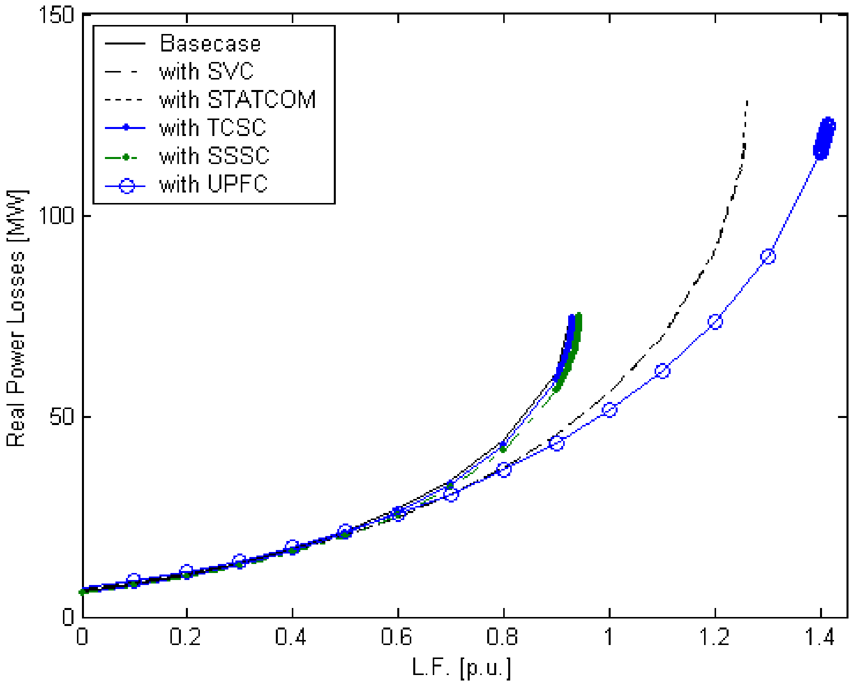
PV Curves and Voltage Profiles

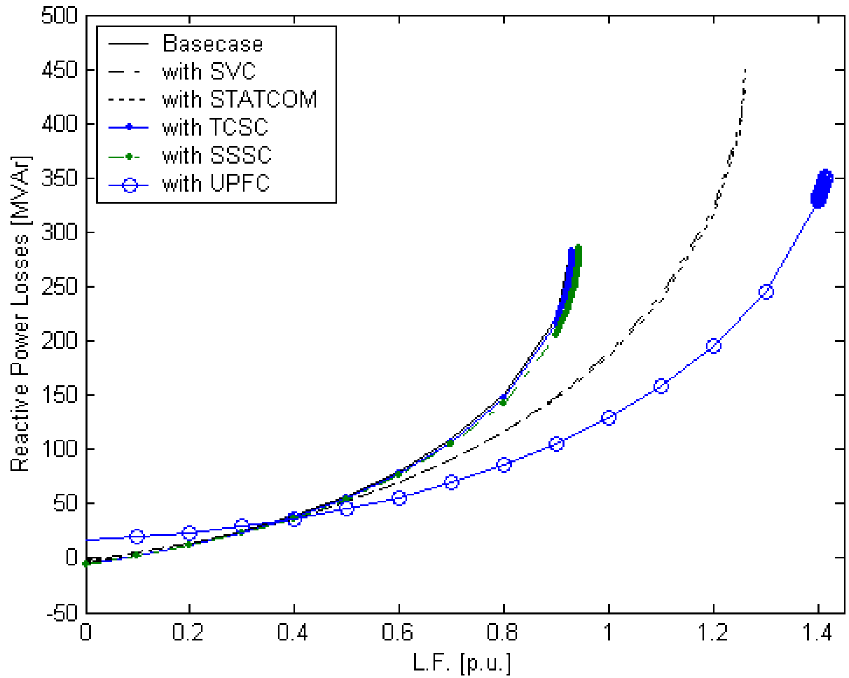
- Voltage profiles close to the collapse point of base case with and without FACTS devices are illustrated in Figure below.



Power Losses

- Both real and reactive power losses follow the same pattern against load increase.





Contingencies

- Comparison of LMs for three worst contingency cases is shown in Table below for various FACTS devices.

Case	Loading Margins [p.u.] for line outages		
	1-2	2-3	1-5
Without FACTS	0.25184	0.38278	0.59605
SVC	0.40205	0.49212	0.87061
STATCOM	0.40097	0.49174	0.86916
TCSC	-	0.4033	-
SSSC	-	0.3964	-
UPFC	0.5003	0.5596	1.0161

Conclusion

- The paper proposes a placement and sizing techniques for seires FACTS devices and UPFC based on reactive power loss sensitivity.
- Influence of various FACTS controllers on static voltage stability margin is thoroughly investigated and compared in the modified IEEE 14-bus test system.
- In the modified IEEE 14-bus test system, UPFC gives the highest loading margin and better performance in terms of voltage stability followed by shunt and series FACTS devices, respectively.
- UPFC followed by shunt and series FACTS devices, respectively, also give the same ranking result in terms of performance for the case of the worst contingencies.

Thank You