A two-stage optimal generator start-up method for power system restoration

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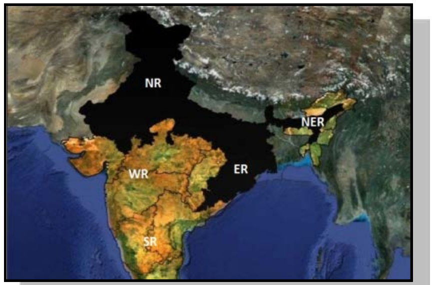
Introduction

- Reliable power supply is becoming more and more important. However, the growing complexity and the inevitable uncertainties in power system operation increase the risks of power system failures.
- A widespread blackout may occur in case of unpredictable disturbances and inappropriate operations. Such as U.S.-Canadian blackout in 2003, Brazilian blackout in 2009 and Indian blackouts in 2012.



Introduction

- The blackout has a severe impact on the economy and society. Effective power supply restoration is an important step toward the self-healing smart grid.
- Load power supply restoration mainly depends on the generator start-up and network reconfiguration.

Previous work

Methods to determine generator start-up sequence

Formulated as a decision-making problem

Solved based on some rules or strategies

Formulated as a combinatorial optimization model

Solved by some multiple mathematical methods

Shortcomings

- The whole start-up sequence of generators is determined based on the same rules or optimization objectives. However, the optimization objectives vary with the restoration process.
- Generator start-up sequence and associated restoration paths are optimized separately. However, the specific restoration paths can affect the determination of the generator start-up sequence.

Proposed two-stage method

During system restoration, the system status is continuously changing.

The optimization objectives of generator start-up sequencing problem vary with the system status.

It is very difficult to optimize the whole generator start-up sequence based on a single model.
A two-stage optimal method for power system restoration is proposed.

Proposed two-stage method

The optimization of the generator start-up sequence is divided into two stages.

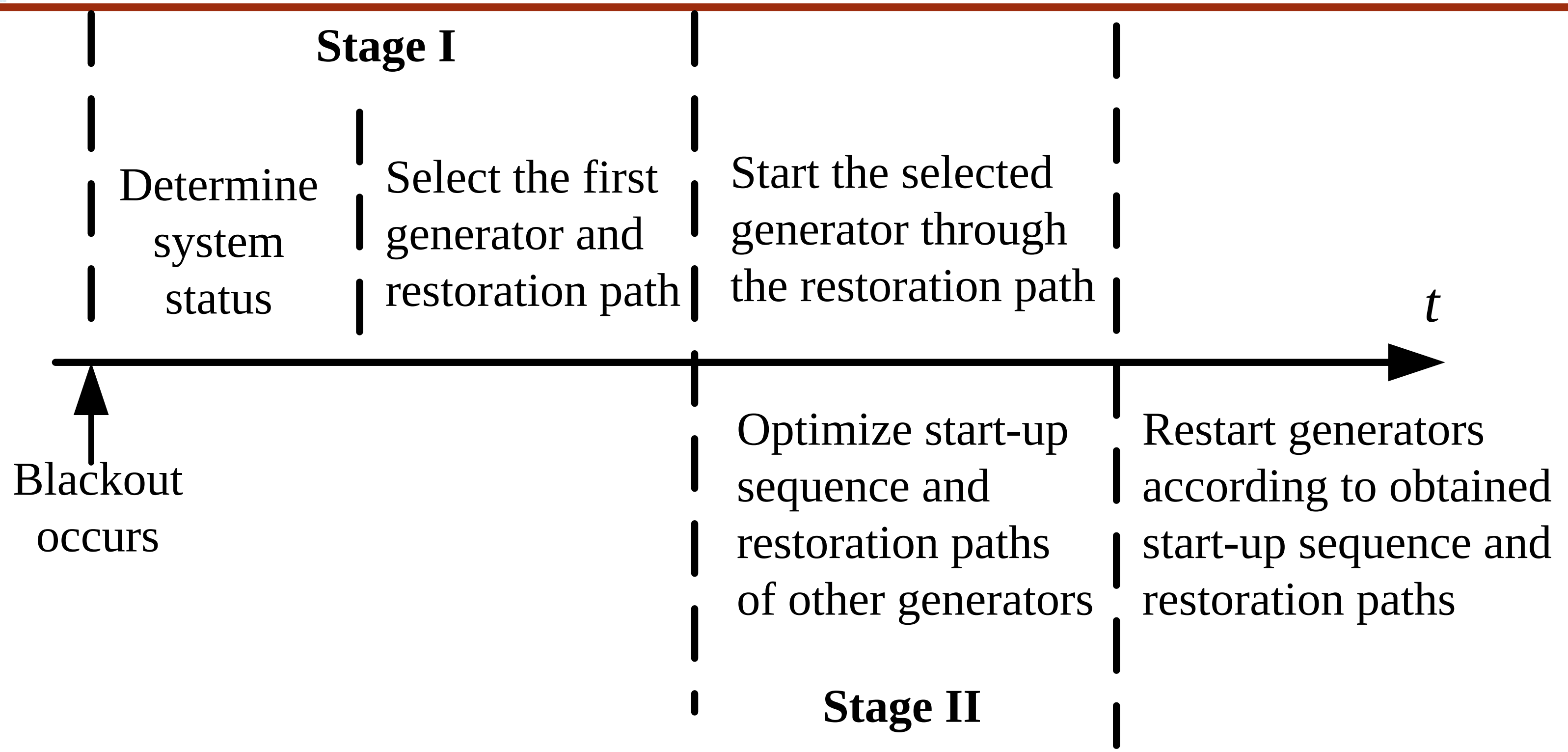
The optimization of generator start-up sequence

Stage I:
System is weak.

Major concern is safe restoration.

Stage II:
System is a little stronger.
Major concern is fast restoration.

Structure of the two-stage method



- After the first generator is selected for safe restoration, actual restoration actions are taken to start the selected generator immediately.
- Meanwhile, the optimization of stage II is carried out in parallel.

Stage I: Selection of the first generator

- The goal:

  To select the first generator for safe restoration in a short time.

- The solving methodology:

  An evaluation index, η is defined to indicate the success rate of starting different generators.

  The generator with the maximum η is selected as the first generator to be started.

The evaluation index

Based on the analysis of restoration actions, η is defined.

Analysis of energizing high-voltage lines → **Line index Lw**

Analysis of switching on no-load transformers → **Transformer index Tw**

Analysis of starting auxiliaries → **Auxiliary index Gw**

$$\eta = L_w T_w G_w$$

Optimization model of stage I

- **Objective**

$$\max \eta$$

- **S.t.**

$$t_{istart} \le T_{HSi}$$

Start-up time constraints

$$\begin{cases} g(x,u) = 0 \\ q(x,u) < 0 \end{cases}$$

The security constraints

- In order to reduce the calculation burden, the generators and corresponding restoration paths are preselected. Establishing a generator set S_G and a restoration path set S_{path}.

Steps to select the first generator

1

- Establish the generator set S_G and the restoration path set S_{path};

2

- Calculate the L_w, T_w and G_w and normalize the indexes respectively. Calculate the η of all plans;

3

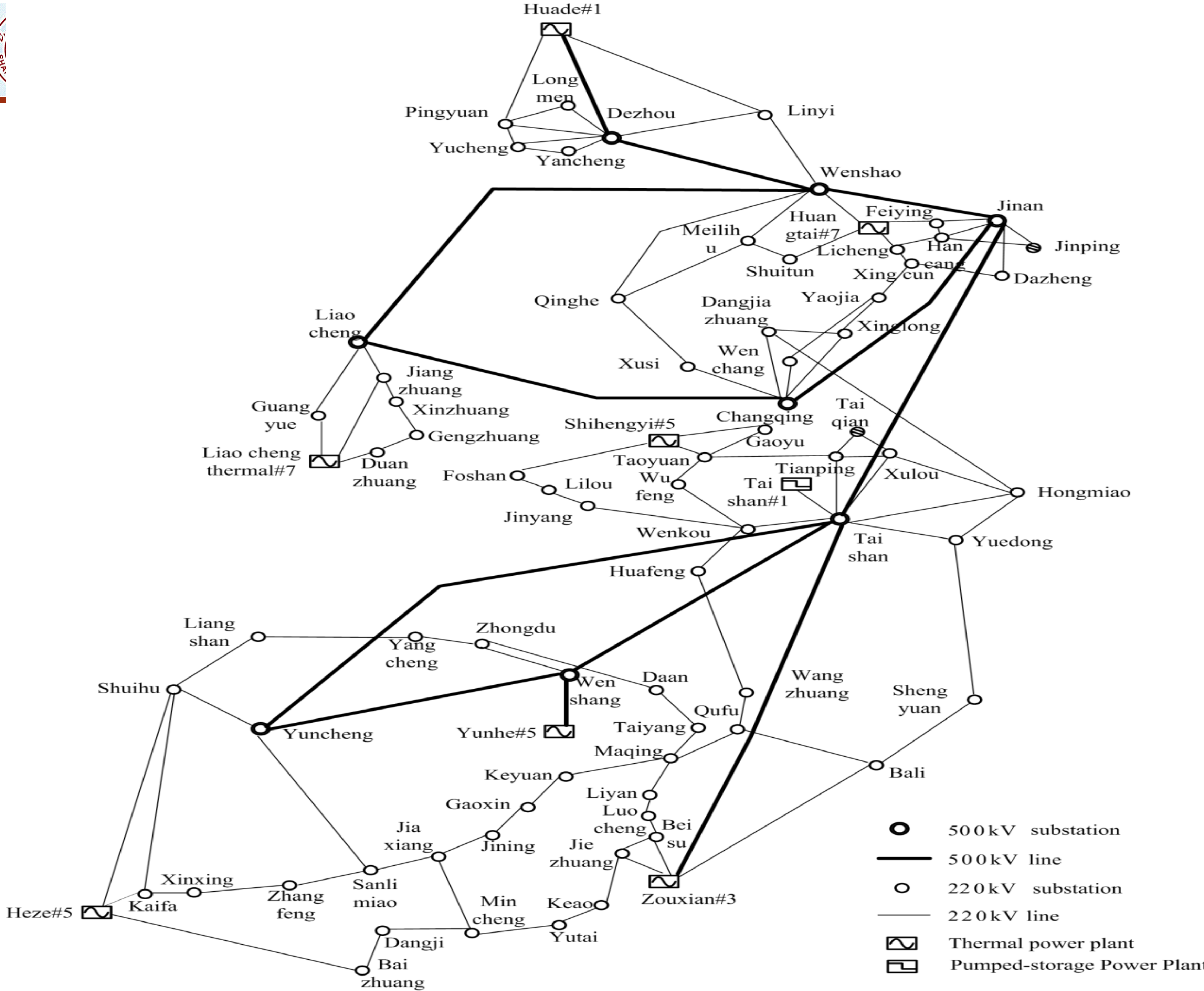
- Select the generator and restoration path with the maximum η, and check the constraints.

Case study

- The western power system of Shandong province is taken as an example for simulation study.
  - 168 stations and 213 lines, voltage level is 220 kV or 500 kV
  - Unit 1 of Taishan pumped storage power plant is an ideal Black Start Generator
- Unit #5 of Shihengyi power plant, Unit #3 of Zouxian power plant, Unit #5 of Yunhe power plant and Unit #7 of Huangtai power plant are put into $S_{G.}$
- For every unit in S_G, three paths are preselected as the candidates which compose S_{path}.

Table 1 The S_G and S_{path}

Plans	S_G	S_{path}
1	Unit #5 of Shihengyi power plant	Taishan Pl.-Taishan Taishan-Tianping Tianping-Taoyuan Taoyuan-Shihengyi Pl.
2		Taishan Pl.-Taishan Taishan-Wenkou Wenkou-Wufeng Wufeng-Taoyuan Taoyuan-Shihengyi Pl.
3		Taishan Pl.-Taishan Taishan-Tianping Tianping-Taoyuan Taoyuan-Gaoyu Gaoyu-Shihengyi Pl.
4	Unit #3 of Zouxian power plant	Taishan Pl.-Taishan Taishan-Zouxian
5		Taishan Pl.-Taishan Taishan-Yuedong Yuedong-Shengyuan Shengyuan-Bali Bali-Zouxian
6		Taishan Pl.-Taishan Taishan-Hongmiao Hongmiao-Yuedong Yuedong-Shengyuan Shengyuan-Bali Bali-Zouxian
7	Unit #5 of Yunhe power plant	Taishan Pl.-Taishan Taishan-Wenshang Wenshang-Yunhe Pl.
8		Taishan Pl.-Taishan Taishan-Yuncheng Yuncheng-Wenshang Wenshang-Yunhe Pl.
9		Taishan Pl.-Taishan Taishan-Zouxian Pl. Zouxian Pl.-Jiezhuang Jiezhuang-Jining Pl. Jining Pl.-Fenghuang Fenghuang-Yunhe Pl.
10	Unit #7 of Huangtai power plant	Taishan Pl.-Taishan Taishan-Jinan Jinan-Wenshao Wenshao-Huangtai Pl.
11		Taishan Pl.-Taishan Taishan-Jinan Jinan-Feiying Feiying-Huangtai Pl.
12		Taishan Pl.-Taishan Taishan-Wenshao Wenshao-Meilihu Meilihu-Shuitun Shuitun-Huangtai Pl.



Huade#1
Long
men
Pingyuan
Dezhou
Linyi
Yucheng
Yancheng
Wenshao
Jinan
Huan
gtai#7
Feiying
Meilih
u
Han
cang
Jinping
Licheng
Shuitun
Xing cun
Dazheng
Qinghe
Dangjia
zhuang
Yaojia
Xinglong
Liao
cheng
Wen
chang
Xusi
Jiang
zhuang
Xinzhuang
Guang
yue
Gengzhuang
Changqing
Tai
qian
Shihengyi#5
Gaoyu
Liao cheng
thermal#7
Duan
zhuang
Taoyuan
Tianping
Foshan
Wu
feng
Xulou
Lilou
Tai
shan#1
Hongmiao
Jinyang
Wenkou
Tai
shan
Yuedong
Huafeng
Liang
shan
Zhongdu
Yang
cheng
Wen
shang
Daan
Wang
zhuang
Sheng
yuan
Shuihu
Qufu
Yuncheng
Yunhe#5
Taiyang
Maqing
Keyuan
Bali
Liyan
Gaoxin
Luo
cheng
Bei
su
Jia
xiang
Jining
Jie
zhuang
Xinxing
Sanli
miao
Zhang
feng
Min
cheng
Keao
Zouxian#3
Heze#5
Kaifa
Dangji
Yutai
Bai
zhuang
500kV substation
500kV line
220kV substation
220kV line
Thermal power plant
Pumped-storage Power Plant

Results

Table 2 The η of all plans

Plans	S_G	L_w	T_w	G_w	η
1	Unit #5 of Shihengyi power plant	0.831	0.846	1.000	0.703
2		0.665	0.846	0.944	0.531
3		0.826	0.846	0.889	0.622
4	Unit #3 of Zouxian power plant	1.000	0.462	0.533	0.246
5		0.474	1.000	0.500	0.237
6		0.473	1.000	0.500	0.237
7	Unit #5 of Yunhe power plant	0.093	0.538	0.833	0.042
8		0.060	0.538	0.778	0.025
9		0.098	0.462	0.667	0.030
10	Unit #7 of Huangtai power plant	0.075	0.462	0.794	0.028
11		0.112	0.538	0.856	0.052
12		0.075	0.462	0.733	0.025

- η of plan #1 is the largest. Unit #5 of Shihengyi power plant is selected as the first generator, and the path of plan #1 is selected as the restoration path.
- Calculation burden is little. The first generator can be selected in a very short time.

The checking results

Table 3 The checking results

Plans	Overvoltages(p.u.)		Self-excitation constrain	Maximum voltage dip(p.u.)	Maximum frequency dip(HZ)
	Sustained	Transient			
1	1.06	2.02	Yes	0.15	0.29
4	1.03	1.74	Yes	0.20	0.43

Table 4 The η of plan 1 and plan 4

Plans	S_G	L_W	T_W	G_W	η
1	Unit #5 of Shihengyi	0.831	0.846	1.000	0.703
4	Unit #3 of Zouxian	1.000	0.462	0.533	0.246

- As seen from the checking results, the defined η is effective.

Stage II: optimization start-up sequence of other generators

- The goal:

  To determine the start-up sequence of the succeeding generators for fast restoration.

- The solving methodology:

  A preference multi-objective optimization model is built.

  The start-up sequence and restoration paths of succeeding generators are optimized simultaneously.

The optimization objectives

The three optimization objectives

The total MWh output

$$f_1 = \sum_{i=1}^{n_G} \int_0^T P_i(t)\,dt$$

The preference objective

The reliability of the restoration paths

$$f_2 = \prod_{j=1}^{n_L} p_j$$

The importance of the restoration paths

$$f_3 = \frac{\sum_{c \in \bar{V}} w(c)}{N}$$

The preference optimization model

Objective

$$\text{Max}: F = [f_1, f_2, f_3]^T$$

A typical preference multi-objective optimization model

S.t.

$$0 < T_{Si} \le T_{HSi} \qquad T_{Si} \ge T_{CSi}$$

Start-up time constraints

$$P_{ci} \le \Sigma P_G(t_0)$$

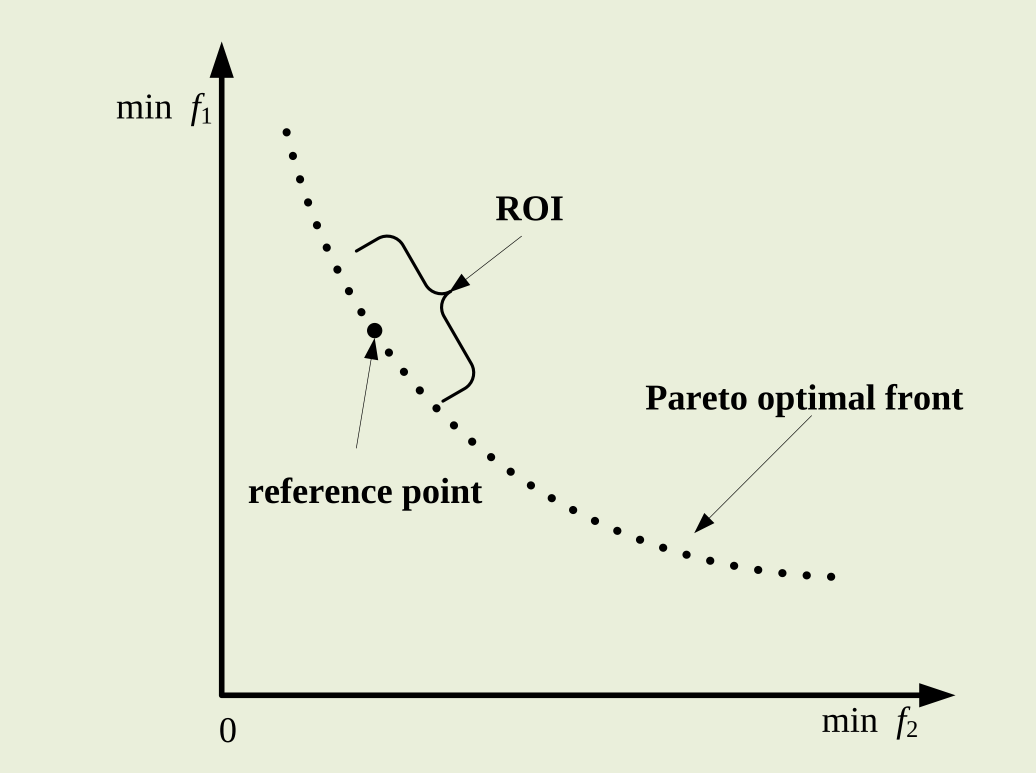
Start-up power constraints

$$\begin{cases} g(x,u) = 0 \\ q(x,u) < 0 \end{cases}$$

Security constraints

Illustration of the preferred region

- **Different from the ordinary multi-objective model, the preference multi-objective model is with preference information. The final goal is to explore only a subset of the Pareto optimal set. The preferred part of the Pareto optimal region, called the region of interest (ROI).**



Reference point

- The first step of solving the preference multi-objective optimization model is to handle the preference information.
- The proposed preference multi-objective optimization model, the preference information is expressed as a reference point in an a priori way.

K. Deb, J. Sundar, U. Bhaskara*, et al.*, "Reference point based multi-objective optimization using evolutionary algorithms," *Int. J. Comput. Intell. Res.*, vol.2, no.3, pp. 273-286, 2006.

r-NSGA-II

- A variant of NSGA-II, denoted as r-NSGA-II, can guide the search toward the ROI based on the reference point.
- The r-NSGA-II is the combination of NSGA-II and r-dominance relation. The relation prefers solutions that are closer to the reference point while preserving the order induced by the Pareto dominance. The weighted Euclidean distance is applied to determine the closeness of a certain solution to the reference point.

$$Dist(x,g) = \sqrt{\sum_{i=1}^{M} w_i \left(\frac{f_i(x) - g_i}{f_i^{\max} - f_i^{\min}} \right)}$$

g_i is the *i*th component of the reference point.

w_i is the weight associated with the *i*th objective.

r-dominance

A solution *x* is said to r-dominate a solution *y* if one of the following statements is true.

- *x* dominates *y* in Pareto sense;
- *x* and *y* are Pareto-equivalent and $D(x, y, g) < -\delta$, where $\delta \in [0,1]$ and

$$D(x,y,g) = \frac{Dist(x,g) - Dist(y,g)}{Dist_{\max} - Dist_{\min}}$$

δ is the non-r-dominance threshold.

$$Dist_{\min} = Min_{z \in P} Dist(z,g)$$

$$Dist_{\max} = Max_{z \in P} Dist(z,g)$$

Initialization of r-NSGA-II

- The structure of individual : Generator start-up sequence and associated restoration paths are optimized simultaneously.

$$(o_1, o_2, .., o_{n_G} \mid A_1, A_2, \ldots, A_{n_{Line}})$$

The sorting operation codes segment is to determine the start-up sequence.

The line selection operation codes segment is to determine the restoration paths.

	Unit 1	Unit 2	Unit 3	Line 1	Line 2	Line 3	Line 4	Line 5
Individual:	0.32	0.46	0.12	0.64	0.72	0.12	0.64	0.55

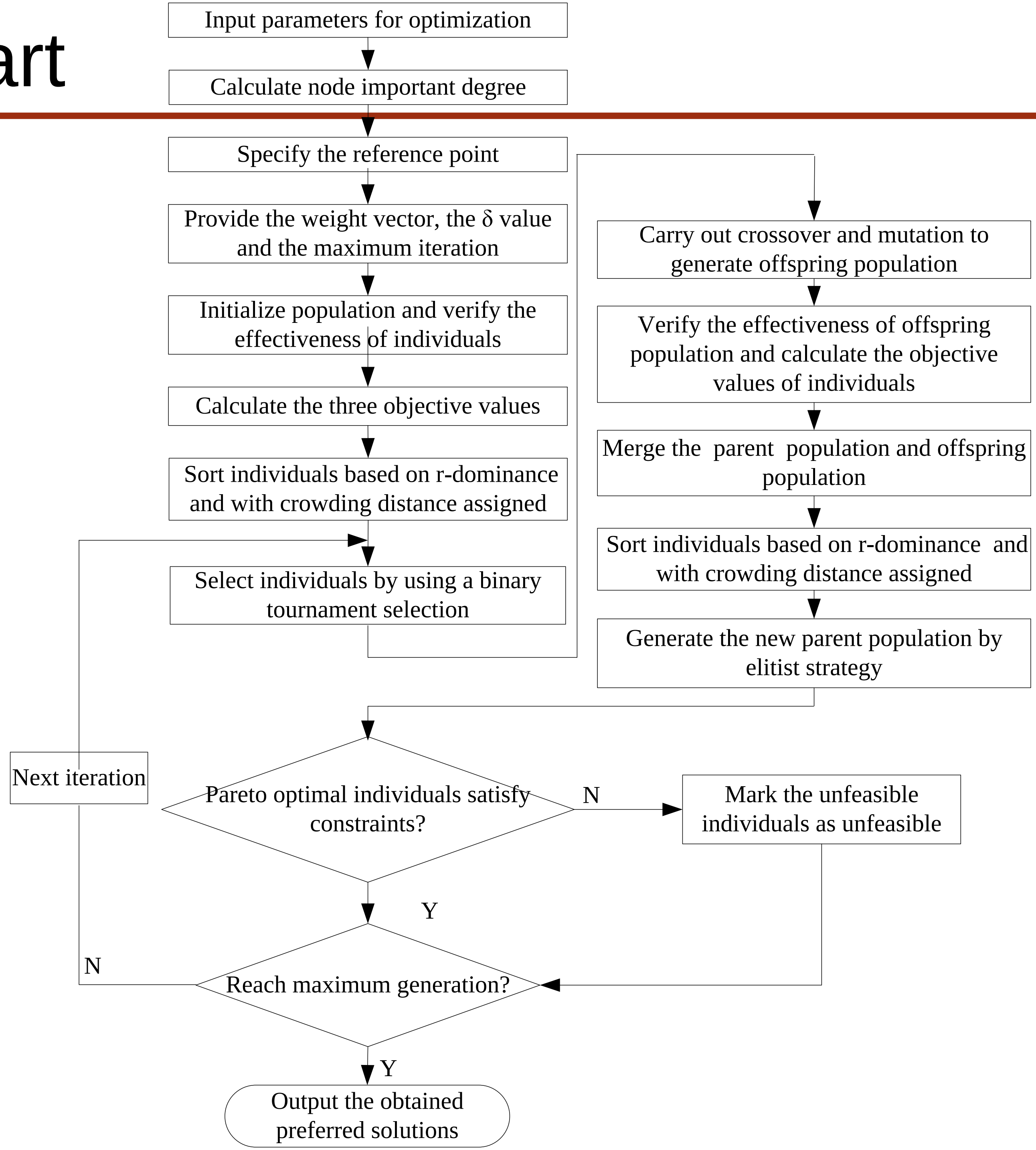
Sequecne:	Unit 3	Unit 1	Unit 2

Selected lines:	Line 1	Line 2	Line 4	Line 5

Initialization of r-NSGA-II

- Verification of effective individual
  - For practical purposes, the selected lines in every individual are required to be topologically connected. After an individual is initialized or updated, the topological connection of individuals should be checked.

Flowchart



Input parameters for optimization
Calculate node important degree
Specify the reference point
Provide the weight vector, the δ value and the maximum iteration
Initialize population and verify the effectiveness of individuals
Calculate the three objective values
Sort individuals based on r-dominance and with crowding distance assigned
Select individuals by using a binary tournament selection
Carry out crossover and mutation to generate offspring population
Verify the effectiveness of offspring population and calculate the objective values of individuals
Merge the parent population and offspring population
Sort individuals based on r-dominance and with crowding distance assigned
Generate the new parent population by elitist strategy
Next iteration
Pareto optimal individuals satisfy constraints?
N
Mark the unfeasible individuals as unfeasible
Y
N
Reach maximum generation?
Y
Output the obtained preferred solutions

Case study

- Unit #3 of Zouxian power plant, Unit #5 of Yunhe power plant, Unit #7 of Huangtai power plant, Unit #5 of Heze power plant, Unit #1 of Huade power plant and Unit #7 of Liaocheng Thermal plant are considered in stage II.

Table 5 The optimal solution of single f_1

Optimal generator start-up sequence	f_1(10^6 kWh)
Zouxian Yunhe Huangtai Huade Heze Liaocheng	4.9431

- Based on the solution of Table 5, the reference point is set as (4.9431×10^6, 0.3173, 0.5088).

Parameters of r-NSGA-II

- The dimension of individuals is 219, the population size and number of maximum iteration take values of 50 and 100, respectively. The threshold, δ is set to 0.3.
- Preferred Pareto optimal solutions.

Plan	Generator start-up sequence	$f_1(10^6\,\text{kWh})$	f_2	f_3
1	Zouxian, Huangtai, Huade, Yunhe, Liaocheng, Heze	4.9431	0.3173	0.5088
2	Zouxian, Yunhe, Huangtai, Huade, Liaocheng, Heze	4.9331	0.3182	0.4692
3	Zouxian, Huangtai, Huade, Yunhe, Heze, Liaocheng	4.8811	0.3191	0.4242

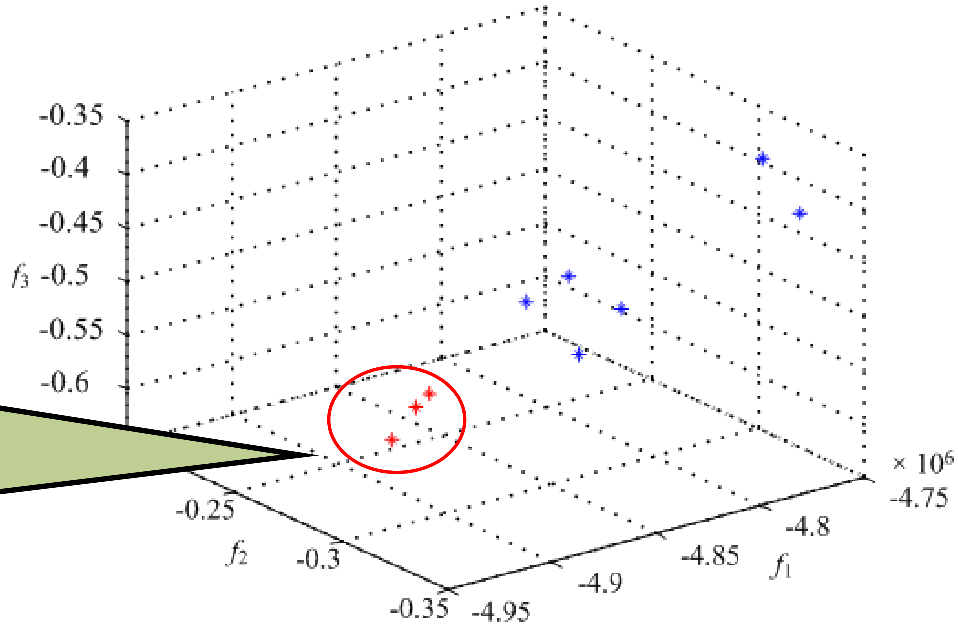
Restoration paths **of preferred solutions**

Restoration path plan	Transmission lines
1	Taishan Pl.-Taishan, Taishan-Zouxian Pl., Taishan-Jinan, Jinan-Wenshao, Wenshao-Huangtai Pl., Wenshao-Linyi, Linyi-Huade Pl., Taishan-Wenshang, Wenshang-Yunhe Pl., Wenshao-Liaocheng, Liaocheng-Guangyue, Guangyue-Liaocheng Pl., Taishan-Yuncheng, Yuncheng-Shuihu, Shuihu-Heze Pl.
2	Taishan Pl.-Taishan, Taishan-Zouxian Pl., Taishan-Wenshang, Wenshang-Yunhe Pl., Taishan-Jinan, Jinan-Feiying, Feiying-Huangtai Pl., Huangtai Pl.-Wenshao, Wenshao-Linyi, Linyi-Huade Pl., Wenshao-Liaocheng, Liaocheng-Guangyue, Guangyue-Liaocheng Pl., Wenshang-Yuncheng, Yuncheng-Shuihu, Shuihu-Heze Pl.
3	Taishan Pl.-Taishan, Taishan-Zouxian Pl, Taishan-Jinan, Jinan-Wenshao, Wenshao- Huangtai Pl., Wenshao-Linyi, Linyi-Huade Pl., Zouxian Pl.-Jiezhuang, Jiezhuang-Jining, Jining-Fenghuang, Fenghuang-Yunhe Pl., Taishan-Yuncheng, Yuncheng-Shuihu, Shuihu-Heze Pl., Wenshao-Liaocheng, Liaocheng-Jiangzhuang, Jiangzhuang-Liaocheng Pl.

Comparison with NSGA-II

To further validate the effectiveness of the proposed method, r-NSGA-II is applied to solve the model.

The red individuals are the solutions obtained by r-NSGA-II



As can be seen, the r-NSGA-II can effectively select the preferred solutions from the whole Pareto optimal set.

5. Conclusions

- Proposed method divides the optimization of generator start-up sequence into two stages and considers different optimization objectives in each stage. In stage I, the proposed method can select the optimal first generator in a short time; In stage II, the r-NSGA-II can effectively handle the preference information and obtain preferred solutions from the whole Pareto optimal set.
- A software is developed for Shandong Power System to produce restoration schemes and training dispatchers.

About Shandong University

- Start from 1901, very early in China colleges, little after Beijing U and Shanghai Jiaotong U
- Comprehensive with a variety of disciplines
- 8 campuses in 3 different cities (Jinan, Qingdao 200miles and Weihai 300 miles)
- 8,000 faculty and staff, 41,000 full-time undergraduates and 19,000 postgraduates
- Among top 10 best colleges in China, toward to the world's highest ranking universities

School of Electrical Engineering

- Start from 1946
- 100 full-time faculty and 35 staff, several part-time faculty, e.g. Wilson Xu, Vladimir Terzija
- 1300 undergraduates, 500 full-time, 500 part-time postgraduates
- Some outstanding alumni

  The CEO of State Grid Corporation of China (SGCC), Mr. Liu, Zhengyao

  The CEO of China Huneng Group, Mr. Cao, Peixi

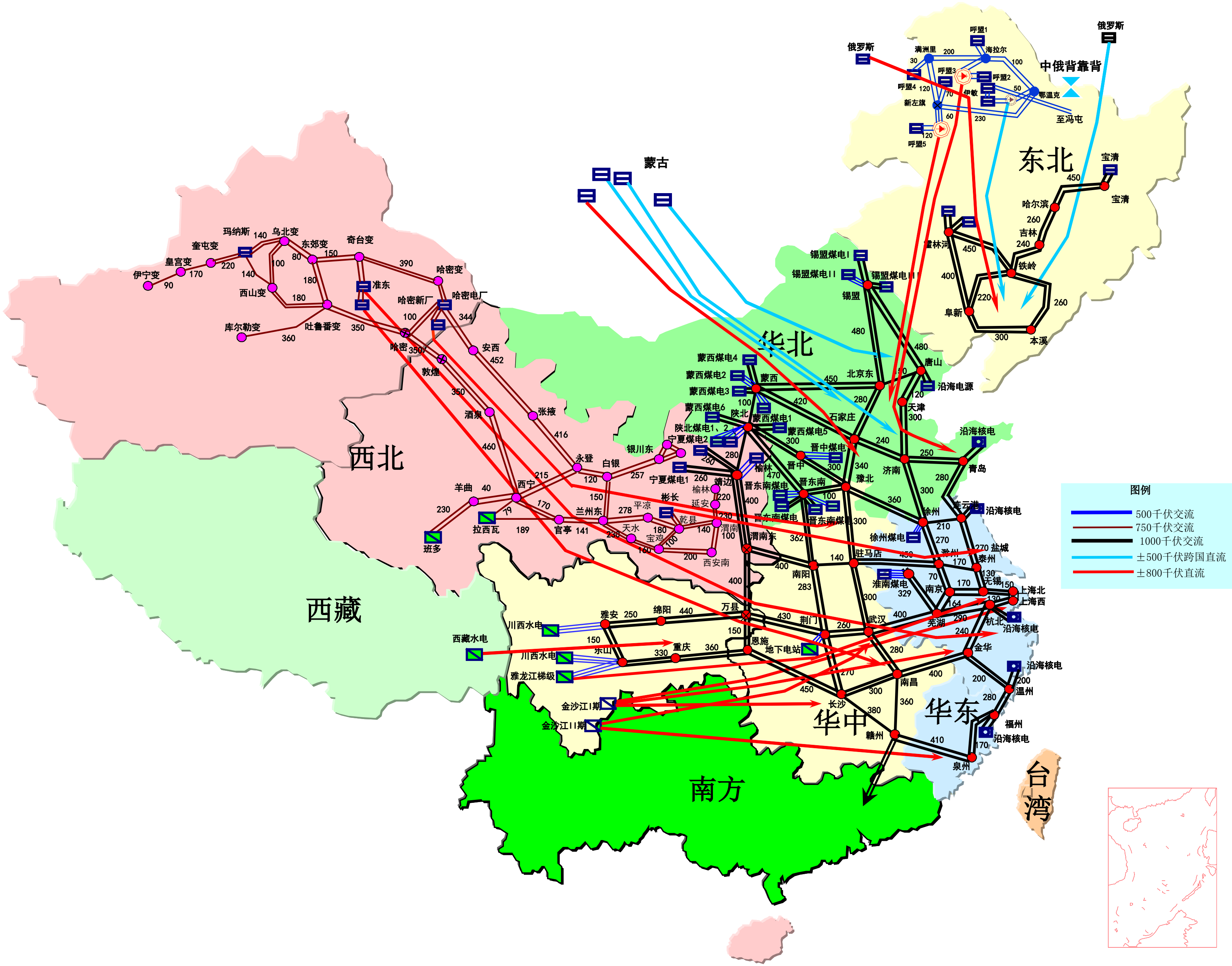
Cooperation with SGCC

Energy Internet

or

Comprehensive Energy network

Network plan of SGCC



Join EE of SDU?

- Scholarship/Chair Professor positions:
  by Mr. Xue, Yusheng (alumnus 1963)
  by Government of Shandong Province
  by SGCC, 3 to 5 positions
  Pay about USD 10000 per month
- Research projects support by the SGCC in Smart grid, renewable energy or very large scale AC/DC power system analysis, optimization and control

Thanks

for your attention !

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