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Flexible Analysis and Control Methods in Smart Grids

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Abstract—**Smart grid puts forward new requirements in the planning, operation and management of power systems. Conventional analysis and control methods with rigid constraints can hardly meet the requirements of flexibility in smart grids. This paper introduces the main existing flexible analysis and control methods in power systems, including flexible alternating current transmission system (FACTS), flexible power network planning, power system operation flexibility evaluation, and demand side management (DSM). Finally, some conclusions are made and further possible applications of flexible analysis and control methods in smart grids are prospected.**

Index Terms—**Flexible analysis, FACTS, flexibility evaluation, DSM, smart grid**

I. INTRODUCTION

With the continuous increasing of power demands and deepening reform of electricity markets, power grids throughout the world are faced with unprecedented challenges. The next generation power grids should meet the requirements on improving resource utilization efficiency, grid operation safety, grid-consumer interaction, etc. Under such circumstances, smart grids are vividly portrayed [1], [2].

However, conventional power system analysis and control methods with rigid constraints can hardly meet such requirements, as there will be much more uncertainties in the future power systems.

Thus, flexible analysis and control methods are proposed. In terms of hardware solutions, there mainly exist flexible AC transmission system (FACTS), dynamic thermal line rating technology, etc. In terms of software solutions, there mainly exist flexible power network planning methods, power system operation flexibility evaluation method, demand side management (DSM), etc.

In this paper, the above mentioned hardware and software flexible analysis and control methods in power system are introduced, from which an overall framework of the existing power system flexible technologies can be given.

II. FLEXIBLE AC TRANSMISSION SYSTEM

FACTS is the earliest application of flexible control technology in power systems, where the flexibility mainly refers to the controllability of node voltage and transmission line current. The definition of FACTS is as follows: technologies based on power electronics that can control electricity quantity and morphology quickly and accurately in the process of electricity generation, transmission and consumption [3], [4].

The keys of flexible power technologies are power electronics technologies, but they are not limited to power electronic technologies. Energy storage technology, distributed power source technology, information processing and control technology, etc are also inseparable.

Controllers in FACTS usually include static var compensator (SVC), static synchronous compensator (STATCOM), thyristor controlled series capacitor (TCSC), static synchronous series compensator (SSSC), thyristor controlled phase shifting transformer (TCPST), unified power flow controller (UPFC), etc.

In conclusion, by using power electronic technology, FACTS enlarge the feasible operation region of power systems and improve their controllability. Thus, grid managers can modify power system to a better operation state. Fig. 1 shows the common steady-state model of a FACTS device [5].

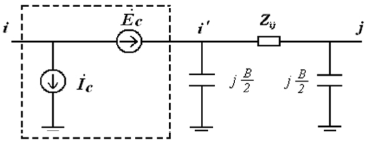

Fig. 1. Common steady-state model of a FACTS device.

However, FACTS cannot be almighty, and there still exist some limitations [6], e.g. the line current increasing ability is limited, the manufacture cost of FACTS controllers is expensive, and there may cause negative effects between FACTS and other power equipments.

Besides, as an extension of FACTS in distribution systems, DFACTS is proposed [7], [8]. Due to the application of IGBT in DFACTS, DFACTS controllers have much faster response characteristics than FACTS controllers. Thus, DFACTS is mainly used to improve distribution power quality.

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III. DYNAMIC THERMAL LINE RATING TECHNOLOGY

Every transmission line in power systems has an associated ampacity or current limit, which is called the thermal capacity or thermal rating. This current-carrying capacity is limited by its maximum design temperature, which determines the maximum sag and the rate of annealing, hence the cumulative loss of tensile [9]. The heat balance equation of a transmission line, which is generally used to calculate the thermal limits, is as follows

$$Q_\mathrm{c} + Q_\mathrm{r} = Q_\mathrm{s} + I^2 \cdot R(T_\mathrm{c}), \tag{1}$$

where Q_c is the convection heat loss; Q_r is the radiated heat loss; Q_s is the solar heat gain; I is the line current amplitude; $R(T_c)$ is the line AC resistance under temperature T_c.

Conventionally, the thermal line rating is determined in a tightly regulated and predictable environment when investments in transmission system were planned many years in advance. However, thermal line rating depends on ambient environments such as temperature, sunshine intensity, wind speed, etc [10]. Such external factors vary almost at any time, so line thermal rating should also be real-time dynamic [11]. Above is the initial motivation of real-time dynamic thermal line rating (RT-DTLR) technology.

RT-DTLR technology was proposed from the late 80s to the early 90s in the last century to relieve the congestion in energy transmission [12], [13]. Researches showed that as static thermal line rating is calculated under worst-case and historical observed conditions, the ratings are consequently conservative for most conditions. Thus, RT-DTLR appears much more reasonable. Experiments show that real-time monitoring of line thermal capability can typically increase the line capability by 10 %–30 % [14]. In [15], an approach to selecting the candidate lines on which an implementation of a DTLR system will have the biggest return was proposed.

In practical applications, a set of monitoring system is installed on the objective line to obtain real-time conductor current and temperature. Meanwhile, a weather station consisting anemometer, wind direction sensor, solar radiation sensor, and temperature sensor is installed, usually at nearby substation. A ground station integrates the data received for the monitoring system and the weather station, and makes data exchange with the supervisory control and data acquisition (SCADA) system.

With the application of RT-DTLR technology, conventional transmission line active power flow constraint limit can be transformed into (2)

$$P'_{l\max} = P_{l\max} + \Delta P_{l\max}, \tag{2}$$

where $P_{l\max}$ refers to active power flow limit; $P'_{l\max}$ refers to the maximum active power flow limit determined by RT-DTLR; $\Delta P_{l\max}$ refers to the increased line capacity.

Now, RT-DTLR technology is considered as an advanced application in smart grids, and it is much closer to practical application. For example, the New York Power Authority (NYPA) is engaging with the Electric Power Research Institute (EPRI) in a demonstration project that will evaluate the instrumentation and dynamic thermal ratings for overhead transmission lines; the electric reliability council of Texas has implemented a dynamic rating application into its energy management system (EMS) [16], etc.

RT-DTLR technology extends the boundary of system feasible region. However, such an extension usually can not completely solve the system transfer congestion. Meanwhile, it brings potential risks to grid security and reliability.

(1) Sag, loss of strength due to annealing, and significant conductor temperature may bring unforeseen risks to grids;

(2) The correlation between single line rating and system load shedding quantity has significant differences among the lines. Arbitrary raise of line rating may waste system utilization and abuse unnecessary system security margins;

(3) According to common experiences, with the approaching of system constraint boundary, system risks increase geometrically.

IV. FLEXIBLE POWER NETWORK PLANNING

Modern power systems are faced with much more uncertain factors than ever. Conventional power network planning methods can hardly meet the requirements in modern power network planning and expansion. Thus, the concept of network flexible planning was proposed.

The definition of electric power network flexible planning is as follows: when planning, consider different kinds of uncertain factors, and then find out an optimal flexible plan, which can make an overall optimization [17].

Uncertain factors in power systems mainly refer to the increment of power load, interest rate, environment constraint, etc. At present, methods describing such uncertain factors include fuzzy method [18], stochastic method [19], grey method [20], blind method [21], etc.

On the other hand, different kinds of mathematics models were proposed to deal with the uncertain factors.

A. Fuzzy Programming Model [22]

Fuzzy rules were first proposed in fuzzy programming models to describe the input and output relationships between different kinds of parameters with different dimensions. Then, network planning evaluation indices can be obtained through fuzzy power flow calculation. Thus, fuzzy programming models can be applied in dealing with multi-objective functions with different dimensions. And the final optimization result is not optimal in one respect, but optimal comprehensive satisfactions.

B. Stochastic Programming Model [23]

Statistical parameters are used to describe the existing power system experiences and laws, and then uncertain factors in the future can be described by probabilistic methods. After that, power flow indices can be obtained using stochastic power flow calculation, which offer evaluation evidences for stochastic planning.

C. Grey Programming Model [24]

Grey method was first proposed to describe systems with part control information. And grey theory pays attention to “small sample and less information” problems, and researches the system character of “intension unclear and extension clear”. Through the whitening process of uncertain factors, they are transformed into certain ones. Thus, they can be solved using certain solution methods.

D. Blind Programming Model [25]

Blind method is a newly proposed method in recent years which can uncertain information with randomness, fuzziness, etc. Blind power flow can be calculated based on blind model (BM) of uncertain factors. And based on such blind information, comprehensive optimal network plans can be solved through cost-effectiveness analysis.

Besides, a lot of algorithms were proposed to solve the models established, such as linear programming [26], integer programming, branch and bound method [27], and modern heuristic methods [28], [29].

V. POWER SYSTEM FLEXIBILITY EVALUATION AND OPTIMIZATION

The concept of flexibility was first proposed in industry design considering uncertainty [30], which refers to the ability that system can resist uncertain factors under certain design parameters. The optimization of system flexibility aims at reducing the negative effects to system operation efficiency caused by uncertain parameters furthest.

Reference [31] introduced flexibility evaluation method into power system analysis, which refers to the controllable degree of the systems under definite system conditions, but not system response ability to uncertain factors such as equipment faults, system accidents, etc. That is to say, flexibility analysis in power systems is deterministic analysis. Then, power system flexibility was divided into four kinds, namely property flexibility, constraint flexibility, load flexibility, and structure flexibility.

Rigid equality and inequality constraints $g(x,u) = 0$ and $h(x,u) \le 0$ are first transformed into flexible forms as (3).

$$\begin{cases} g(x,u) = \varepsilon_g, \\ h(x,u) \le \varepsilon_h. \end{cases} \tag{3}$$

In flexibility evaluation and analysis, flexible constraint boundary values ε_g and ε_h are parameters with variable values. And their values are closely related with system constraint flexibility. Then, a power system operation flexibility evaluation index was given

$$\begin{aligned} &\max \delta, \\ s.t.\ &g(x,u) = 0, \\ &\underline{h} + \delta\Delta h^{-} \le h(x,u) \le \overline{h} - \delta\Delta h^{+}. \end{aligned} \tag{4}$$

It is obvious that the bigger the value of δ is, the larger feasible region the system has, which also means the stronger adjust ability the system has. As flexibility index from one scale is not reasonable enough to evaluate a system with different kinds of constraints, an improved multi-scale flexibility index δ_M is proposed.

Then, flexible comprehensive optimization models with different flexible constraints are discussed in [31]–[33], where the conflict between power system operation security and economy can be compromised.

VI. DEMAND SIDE MANAGEMENT

Interaction is one of the most important characters of smart grid. To realize such an interaction, power loads must be transferred to active participants in power system management. Flexible power loads have important practical significances in modern power systems.

Firstly, renewable energies (mainly wind power) are accessing power grids in a large scale. However, wind power has strong randomness, big amplitude of fluctuation and apparent intermittent. In extreme cases, wind power changes from zero to 100 %. Such characters cause a comparatively lower utilization of wind power. If power loads can adjust their power according to the fluctuation of wind power, the passive influence of wind power can be relieved and its utilization can be improved [34].

Secondly, interaction can modify power system operation economy and security. In smart grids, a grid incentive mechanism is established by applying real-time pricing. In such a mechanism, power loads are encouraged to move from peak load to valley load. Such a change can largely improve system operation economy. On the other hand, extreme heavy loads are more likely to cause system operation accidents. In conventional power systems, load shedding acts as the last line of defense against power system instability. If power loads can participant in system management, they can make active avoidances, thus, the occurring of load shedding can be largely reduced.

Thirdly, interaction benefits electric vehicle charge and discharge. Electric vehicles gain quick developments in recent year as their huge potential in reducing carbon dioxide emission and energy-saving. However, if they are not well controlled, they can bring negative influence to power grids as their uncertainties in electricity charging. Research shows that large-scale unordered charging can increase distribution grid power loss and deteriorate power quality. Conversely, if the charging actions are coordinated optimized, charging in load peak can be removed, and the negative influence can be relieved.

To realize such an ‘interaction’, current electric network should be upgraded, and the modern smart grid contains both advanced power grid and communication grid. The overall framework of smart electric power grid and communication grid is shown as Fig. 2.

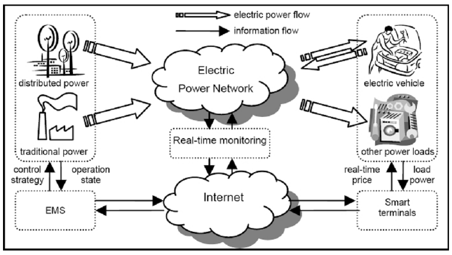

Fig. 2. An overall framework of smart electric power grid and communication grid.

Boulder, Colorado, USA is the first smart grid city in the world. In Boulder, smart meters are installed to every family. According to real-time pricing, people can adjusted some of their households (e.g. washing, ironing) to load valley so as to save electric charges.

Interaction between power grid and load in smart grids mainly reflects as follows.

In Japan, the development and application of solar energy is their focus of smart grid. Their long-term goal installed capacity of solar energy is 28 GW and 53 GW in 2020 and

2030, respectively. Meanwhile, they proposed the concept of ‘energy information’, through which the utilization of family and community power are to be improved.

TABLE I. COMPARISON BETWEEN CONVENTIONAL GRIDS AND SMART GRIDS IN GRID-LOAD INTERACTION.

	Conventional Grids	**Smart Grids**
Network flow	One-way energy flow	Highly integrated energy, information and business flow
Grid structure	Electric network	Electric network & communication network
Dispatching strategy	According to load forecasting	According to real-time load feedback
Price mechanism	Fixed, tiered or time-dependent price	Sufficient price information, real-time price
Crisis management	Load shedding	Load active avoidance

In China, Beijing, Xiamen, Hangzhou and Yinchuan were selected as the first four smart grid pilot cities. In these cities, smart generation, smart distribution, smart consumption and smart dispatching are experimented.

VII. CONCLUSIONS

FACTS, flexible power network planning, power system operation flexibility evaluation, and DSM are the most popular used flexible technologies in current power systems. They break the rigid constraints in conventional power systems analysis and find solutions to deal with uncertain factors in practical power system operation.

In next generation smart grids, flexible analysis and control methods must have further development, especially in the fields of renewable energy access, peak load shifting, system operation efficiency improving, etc.

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