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Research on Improving Quality of Electricity Energy in Train's Traction

Huang Yuanliang
Jinan University
China

1. Introduction

To serve as one of the main transportations and carriers of the world nowadays, electrified railway is developing rapidly in its speed and length of line. In order to improve the power supply capability and power quality of traction system, scientific researchers have put forward many methods. Adding shunt capacitor compensator or series capacitor compensator in traction system are both effective methods. They can filter, regulate voltage, raise the utilization rate of the power supplying equipment capacity, and improve power factor.

This section will analyze the performance of power supplying capability increased equipment and the influence of each other, besides, study the strategy of coordinated control.

2. Shunt capacitor compensation of traction power supply system

Shunt capacitor compensation of traction power supply system means to connect a capacitor group and control device in parallel on feeder line or supply arm so as to improve power factor and power quality. Now dynamic capacitor compensation is used primarily.

2.1 Principle of shunt capacitor compensator

The connection and equivalent circuit diagram of shunt capacitor compensator is shown as figure 1, where $\dot{U}_1$ is supply voltage, and γ_1+jW_1 is each phase impedance of power that converting into low-voltage side by internal impedance, line impedance and traction transformer. $\dot{U}_2$ is traction bus bar voltage of traction substation, X_c is capacitor of shunt compensative capacitor banks, X_L is inductance of reactor connected with capacitor group in series, Z is traction load impedance, I_c is static var compensator current of shunt condenser, and I_q is current of traction load. Before installing traction shunt capacitor compensator, current flow through the traction transformer is,

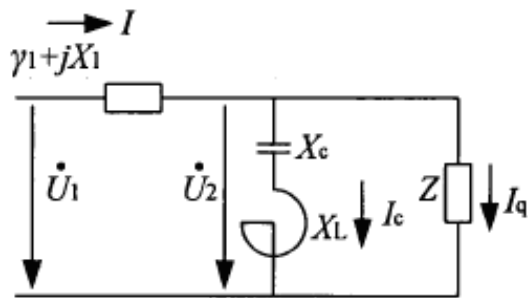$$I_q = \frac{\dot{U}_1}{Z + \gamma_1 + jX_1}$$

Fig. 1. Chart of traction power supply shunt capacitor compensator

After installing, the current flow through the traction transformer is,

$$I = \frac{\dot{U_1}}{\dfrac{Z * j(X_C + X_L)}{Z + j(X_C + X_L)} + \gamma_1 + jX_1}$$

As two equations above indicates, after installing, the current flow through the traction transformer I_q reduces to I, active power remains unchanged, and reactive power decreases.

$$P = \dot{U_1} I_q \cos\Phi_1 = \dot{U_1} I \cos\Phi_2$$

$$Q_1 = \dot{U_1} I_q \sin\Phi_1$$

$$Q_2 = \dot{U_1} I_q \sin\Phi_2 < Q_1$$

It can be seen from 3 equations above, after installing, traction power factor can increase from $\cos\Phi_1$ to $\cos\Phi_2$.

As figure 2 shows,

$$I_C = I_q \sin\Phi_1 - I \sin\Phi_2 = P(\tan\Phi_1 - \tan\Phi_2)/U_1$$

While $I_C = U_1 \div X_C = 2\pi fCU_1$, in order to make power factor increase from $\cos\Phi_1$ to $\cos\Phi_2$, the capacitor it needs to compensate is capacitor C,

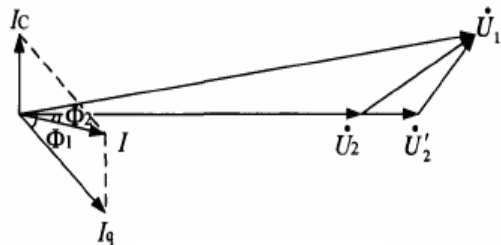$$C = P(\tan\Phi_1 - \tan\Phi_2) \div (2\pi fU_1^2)$$

Fig. 2. The column picture of parallel compensation

In Traction Power Supply system, when calculating and defining the capability of shunt capacitor, we should be based on the maximum average of traction load to choose shunt capacitor.

2.2 Dynamic shunt capacitor compensator

Nowadays in order to track changing traction loading timely, provide with rational reactive power compensation, and save the energy cost, dynamic compensator with shunt capacitor is widely used in electric railway. There are 3 commonly used devices.

2.2.1 Static var compensator (SVC)

The immediate purpose of parallel var compensator is to lower reactive current and negative sequence current. Three-phase SVC is an effective mature technology of improving harmonics, negative sequence and voltage fluctuation caused by the load of electric railway. SVC is by means of thyristor controlled reactance (TCR) and the strategy of three-phase balanced control based on "Steinmetz" to make dynamic reactive power compensation, control voltage, and improve negative sequence. This method can not only balance three-phase reactive power, but also balance three-phase active power. Therefore, it is an effective method.

2.2.2 Static synchronous compensator (STATCOM)

In contrast with SVC, STATCOM has its advantages of fast speed, great loading rate adaptation, high work efficiency, and small output harmonic content. Especially, adopting two-phase structure can achieve four-phase control of active and reactive power, provide two supply arms of power substation with dynamic reactive compensation, besides, regulate active flow of two supply arms, so as to dynamically balance the loading.

Since 1980s, the researches on the technology of STATCOM dynamic voltage compensation have become one of the hot topics in the field. Because STATCOM is usually supported by DC voltage provided by capacitor on DC side, it can't provide continues active power. But if change a power supply on DC side, STATCOM, served as voltage source inverter, can exchange energy with system. Connect a single-phase converter on both supply arms of Scott transformer, which are interconnected through intermediate links. The work mode of controlling two transformers makes them be DC power supply of the other one so as to achieve active power facility between both supply arms. When adopting impedance matching balance transformer or Scott wiring transformer, active load of both supply are balanced. Therefore it can eliminate the negative sequence completely. Accordingly, in order to achieve power factor compensation and negative sequence improvement of traction substations, we can install two single-phase STATCOM on traction transformer secondary side to carry on reactive compensation and phase transformations of active power.

2.2.3 Static var generator/ absorber (SVG)

Compared with traditional SVC, the regulation speed of SVG is faster, and the range of operation is wider. Besides, adopting multiplex, multi-level or PWM can significantly reduce the content of harmonics in compensation current. More importantly, because of the smaller size of capacity cell in SVG, the size and cost will reduce greatly.

The basic principle of SVG is connecting self-communicated bridge circuit in parallel on grid or through a reactor, then regulating the phase and amplitude of output voltage of bridge circuit on AC side or controlling the AC current directly to make the absorption and output of reactive current meet the demands. Finally achieve dynamic compensation. Because SVG converts the DC side voltage to AC side output voltage which has the same frequency with the grid through the switching of power semiconductor, just like a voltage-type inverter, when considering fundamental frequency, SVG can be seen as an AC voltage source whose phase and amplitude could both be controlled. It is connected on power grid through AC reactor. The working principle is shown as figure 3.
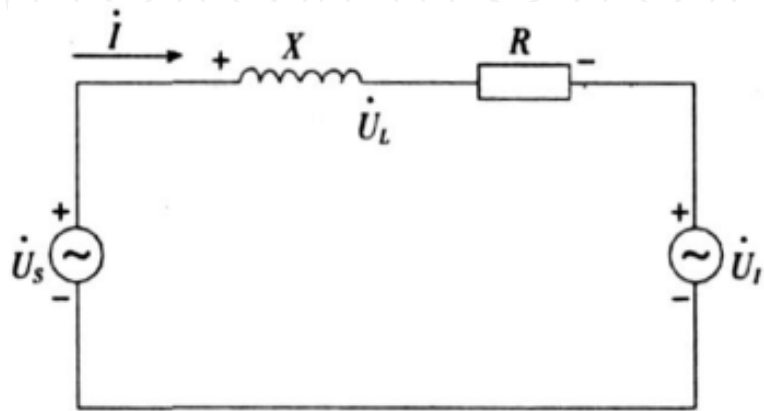

Fig. 3. Single-phase equivalent diagram

The output AC voltage of power grid and SVG are $\dot{U}_s$ and $\dot{U}_I$, and the voltage of reactance X is $\dot{U}_L$. It is the phasor difference of U_S and U_I. The current I, flowing through reactance X, absorbed from power grid by SVG, is controlled by voltage of reactance. Hence converting the amplitude of U_I on AC side and the relative phase with U_S can convert the voltage of reactance so as to control the phase and amplitude of current absorbed by SVG, and the nature and size as well. Using appropriate control methods can control the currents running through each branch in three-phase bridge converter circuit individually, and make energy storage capacitor absorb energy from light load, and release energy to heavy load, so as to compensate for reactive power and negative sequence of traction load at the same time. If adopting PWM with appropriate testing method, it still can active filter.
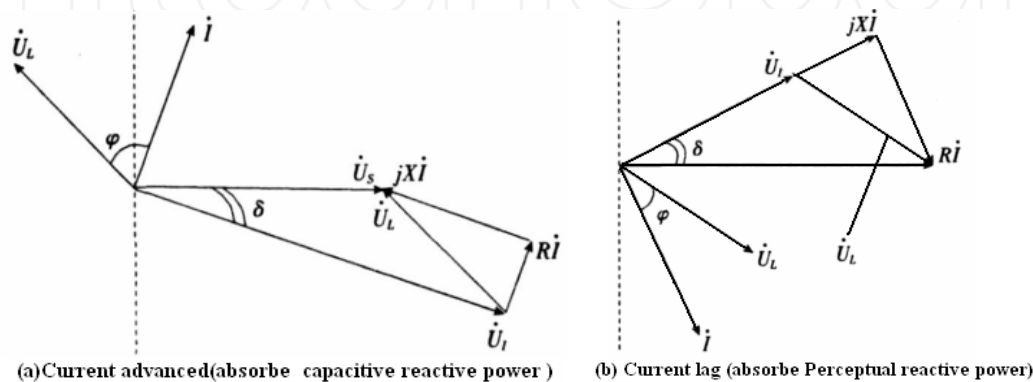

(a)Current advanced(absorbe capacitive reactive power)   (b) Current lag (absorbe Perceptual reactive power)

Fig. 4. The original vector graphics of SVG

3. Series compensator of traction power supply system

Series compensation of Traction Power Supply system is a capacitor group and control and protection device connected on feeder line or supply arm. Its function is to raise terminal voltage of supply arm and the power factor, then improve power quality.

3.1 The principle of series compensator of traction power supply system

Connect a capacitor in series on traction substation or power-supply section. The capacitor could offset part of inductance of Traction Power Supply system, and reduce voltage loss. The voltage loss is:

$$\Delta U_C = -IX_C \sin\varphi = -I\sin\varphi \cdot X_C .$$

Where φ is the angle between load-terminal current vector and voltage vector.

The voltage loss is negative when load current running through series capacitor. It means output voltage of capacitor is greater than entrance voltage. The effect of voltage improvement has some connection with load current and power factor. The higher the load current, and the lower the power factor, the better the effect. The absolute value of voltage loss of capacitor is proportional to load current. It has automatic regulation to the voltage of supply arms, which is compatible with the drastic changes of the load of electric traction.
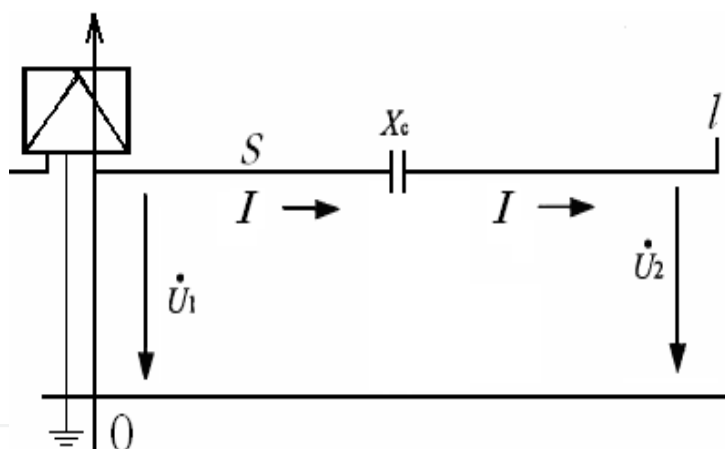

Fig. 5. The graphic of Series Compensation of Power-Supply System of Electric Traction

The installed capacity of the series compensation is decided by its rated current and rated voltage. Series compensation is different from other electric devices for its working voltage is proportional to its current. Therefore, when choosing the content of the series compensation, the higher the rated current, the lower the working voltage. It means the lower the compensative voltage, the worse the compensative effect. That is the compensative effect is in inverse proportion to the installed capability

The working voltage of series capacitor is proportional to its current. When choosing the series capacitor, the higher the rated current, the lower the working voltage. It means the lower the compensation voltage, the worse the compensation effect. The compensation capability is in inverse proportion to the installed capability. So the key point to meet the demands of compensation effect is to choose the rated current of series capacitor.

Series capacitor X_C can be calculated through rated voltage U_{CN}, rated current I_{CN}, and the power factor $\cos\varphi$ of the line. $X_C = \dfrac{U_{CN}}{I_{CN}}$, that is,

$$\Delta U_C = I_C \cdot \frac{U_{CN}}{I_{CN}} \sin\varphi = I_C \frac{U_{CN}^2}{Q_{CN}} \sin\varphi$$

Obviously, when the rated voltage U_{CN} and the current flows through are the same, the higher the I_{CN} (Q_{CN}), the lower the ΔU_C. ΔU_C is proportion to I_{CN} (Q_{CN}).

In order to meet the demands of compensation effect, the key point is choosing the rated current of series capacitor.

3.2 Thyristor controlled series compensation capacitor

Thyristor controlled series compensation capacitor includes Thyristor Switched Series Capacitor (TSSC) and Thyristor Controlled Series Capacitor (TCSC) commonly.

TSSC is consisted of a series of series capacitor. Each capacitor is connected with a transistor valve, which has a pair of anti-shunt transistors. TSSC adopts discrete step to increase or decrease the connected capacitor so as to control the compensation capacitor.

TCSC is a good way of series compensation, which is consisted of a series capacitor and a thyristor controlled reactor L. Actually, TCSC is also consisted of a protective device. It is shown as figure 2.

When the thyristor is turned off completely, the reactor is at non-conducting state, and TCSC manifests itself as a series capacitor compensator. When the conduction angle of thyristor is increasing gradually, the capability of the reactor of circuit branch and capacitor connected in parallel is increasing as well. When the reactor reaches the size of capacitor, shunt parameter will resonate, and the impedance of TCSC will be infinite. When the conduction angle of thyristor is increasing further, TCSC is manifesting itself as an inductive impedance, and the inductive impedance is decreasing gradually. When the thyristor is conducting completely, the impedance is the least. Therefore, TCSC can provide capacitive or inductive equivalent impedance within a certain range by controlling the conduction angle of thyristor.
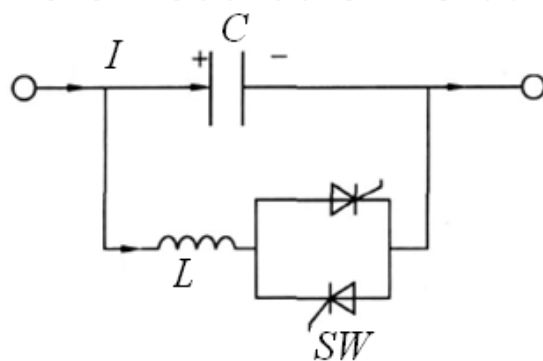

Fig. 6. The structural drawing of TCSC

4. Unified power flow controller (UPFC)

The UPFC consists of two voltage-sourced AC-DC converters connected back-to-back with some means (e.g., a chopper or specially designed1 converters) to permit interchange of power between the two converters.

Research work directed to analyze and build a scaled model of the UPFC has been sponsored by the Western Area Power Administration, the Electric Power Research Institute, and the Westinghouse Science and Technology Center. Refer to figure 7 for details.

Among the unique capabilities of the UPFC is the ability to control the flow of both real and reactive power on its series transmission line simultaneously and independently, as well as the ability to control bus voltage by operation of its shunt (STATCOM) element.

5. The interaction and coordinated control of traction power supplying system capability increased devices

5.1 The interaction between devices

Take the interaction between Thyristor Switched Capacitor (TSC) and series compensation of Traction Power Supply system for example to explain the interaction between ordinary equipments of the system. The circuit of power-supplying capacity increased system of electric traction which has dynamic shunt compensation equipment and series compensation equipment is shown as figure 8. I_q is the current of traction loading.
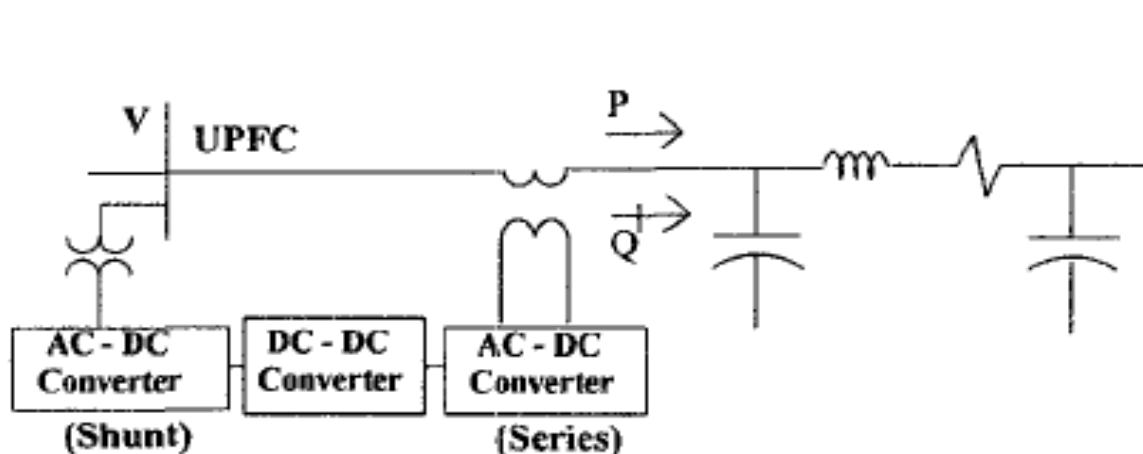

Fig. 7. Unified Power Flow Controller (UPFC), with DC-DC converter between the self-commutated AC-DC converters
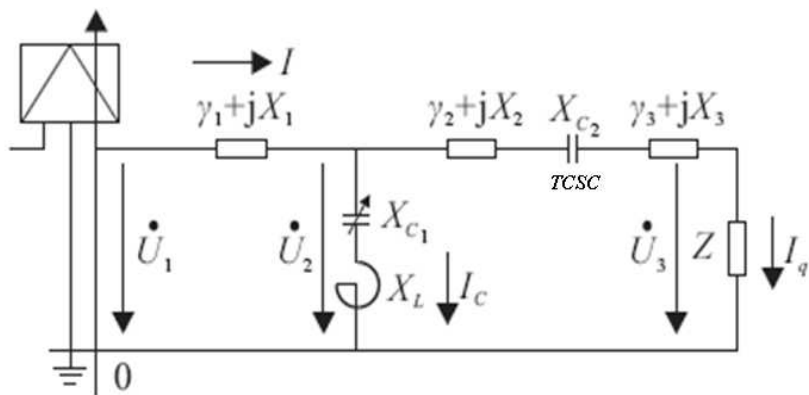
Fig. 8. Figure of power-supplying capacity increased system of electric traction

Let me describe the interactions between them. Assume the voltage of high side of traction substation is $\dot{U}_S$, the voltage of low side is $\dot{U}_1$, while main transformation ratio is k. Other parameters are shown in figure 8. Before installing the dynamic shunt compensation equipment, system current $I = I_q$, and the system can be described as：

$$\dot{U}_1 = \dot{U}_3 + [(\gamma_1 + \gamma_2 + \gamma_3) + j(X_1 + X_2 + X_3 - X_{C2})]\dot{I}_q$$

After installing TSC, following changes occur：

a.   The power factor changes from $\cos\Phi_1$ to $\cos\Phi_2$.

The power factor increases from $\cos\Phi_1$ to $\cos\Phi_2$ after paralleling a capacitor X_c.

$$X_C = P(\tan\Phi_1 - \tan\Phi_2) \div (2\pi f U_1^2)$$

b. $\dot{U}_1$ increases.

Since TCS generates a compensative current contrary to the reactive component, the current flows through $\gamma_1 + jX_1$ is decreasing, and a voltage rise appears in $\dot{U}_1$:

$$\Delta U_1 = (\gamma_1 + jX_1)I(\sin\Phi_1 - \sin\Phi_2)$$

c.   The reactive power absorbed from system by transformer increases.
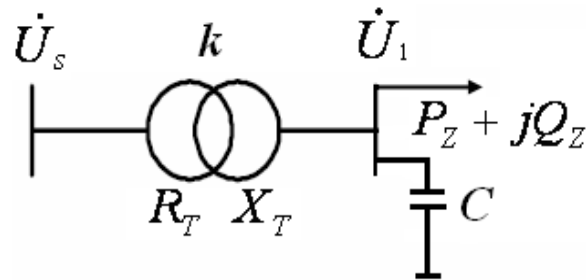
It is shown as figure 9.

Fig. 9. Circuit of transformer of power-supply system of electric traction

$$U_S - U_1 = (Q_z X_T) \div U_1$$

So

$$Q_z = (U_S - U_1)\ U_1 \div X_T$$

Because $U_S = kU_1$, therefore,

$$Q_z = (k-1)\ U_1{}^2 \div X_T$$

It can be seen from the equation above: The reactive power absorbed from system by transformer is proportional to its voltage. When the voltage increases from U_1 to ΔU_1, the reactive power absorbed from system by transformer increases as well.

$$\Delta Q_z = (k-1)[\ (U_1 + \Delta U_1)^2 - U_1{}^2] \div X_T = (k-1)[\ 2U_1 * \Delta U_1 + \Delta U_1{}^2] \div X_T$$

d. The current flowing through the series compensation decreases, and it leads to decrease of the terminal voltage of supply arms.

The series capacitor X_C can be calculated by the rated voltage of series capacitor U_{CN}, the rated current I_{CN}, and the power factor $\cos\Phi_1$. If the current flowing through the series compensation is I before installing the parallel devices, the compensative voltage is:

$$\Delta U = I \times X_C \sin\Phi 1$$

After installing TSC, if the current flowing through the series compensation is $I + I_C$, because of the contrary direction of the reactive current I_C and I we can get $|\ I + I_C\ | < |\ I\ |$, so

$$\Delta U' = |\ I + I_C\ | \times X_C \sin\Phi_2 < |I| \times X_C \sin\Phi_2 < |I| \times X_C \sin\Phi_1 = \Delta U$$

It means the compensative capacity of the series compensation will decrease after installing TSC, and can't meet the expectations of compensation effect.

e. The active power loss of the system increases.

From the respect of TSC only, the increased active power loss is:

$$\Delta P = X_C \operatorname{tg}\alpha$$

α is the dielectric loss angle of the capacitor.

From the above analysis, if seeking a coordinate control strategy without proceeding from the entire system, each control system will disturb others mutually, and then lead to the difficulty of reaching ideal operating condition.

Adopting TCSC and thyristor controlled parallel capacitor in Traction Power Supply system, and optimally distributing the capacity of TCSC and thyristor controlled parallel capacitor according to the real-time condition of electric traction can not only save power, improve the power quality of Traction Power Supply system, but also protect the equipments, increase the safety of operation of trains. Solving the problem of coordinately control the electric traction reasonably is meaningful for the development of Traction Power Supply system.

5.2 Common analytical methods of interaction

Traction Power Supply is a kind of flexible AC transmission mode. The technology of Flexible AC Transmission System (FACTS) is one of the most attracting directions of nowadays new technology of power system. It becomes an effective method of solving the problems of economic operation, security and stability in power system.

Nowadays in the field of interaction analysis of FACTS, mainly there are two kinds of methods: ①Simulation of nonlinear time-domain. This method can only observe some sever interaction through simulation waveforms, while can't obtain accurate quantitative analysis. ②Traditional modal analysis of characteristic root. This method can study the influence on system from FACTS. Its objects mainly focus on the changes of one or some oscillation modals. However, it can't obtain quantitative analysis of the degree of interaction among controllers.

In the last 30 years, research on interaction has attracted widely focus. There are many documents in the field of analysis of steady-state and dynamic interactive control. Introductions of analytical methods of interaction are shown below.

5.2.1 Analytical method of modal

As a traditional analytical method, analytical method of modal has been widely used in controlled field. It also gets a lot of achievements in the research on the analysis of interaction among power system equipments. The analysis of sensitivity of characteristic root is one of the important achievements of analytical method of modal. It represents the strength of the changes of characteristic root caused by every parameter. The real component stands for damping capacity for modal oscillations. If the real component is positive, it means instable. The imaginary part stands for the frequency of natural oscillation.

Traditional analytical method of modal is built on characteristic root solved of entire state equation (Full-dimension analytical method). When the order of the state equation is 200, QR algorithm which usually considered effective can't get the right characteristic root. In order to overcome the shortcoming of Full-Dimension Analytical Method, reduced dimension analytical technology gets certain research. We get analytical method of modal through the state equation after reducing dimension. The equation has the characteristic root and characteristic vector which need studying. Reference [3] separated the modal, then got a system transfer function that include main modal only. Based on it, put forward multiple indicators of site selection and designation of controller of FACTS. Even though these indicators aren't accurate, the order of the system reduces effectively.

Recent years, with the development of non-linear system theory and application of modern mathematic methods, as a successful mathematical analysis tool and linear modal analysis, Normal Form (NF) is widely used in the analysis of mode interaction, study on stability region of system, and the designation of controller. Reference [4] put forward an analytical technology to reduce the order of state equation of system to second-order equation near working point and revealed the interaction among modals. NF provides new way for site selection and designation of controller. Reference [5] adopted NF to predict the separating phenomenon of oscillation modals in regional system. It revealed the importance of the influence on the stability of system from non-linear factors. Reference [6] and [7] put forward a research method of using NF mathematical tools to analyze the interactions among controllers

of FACTS. Linear analysis ignores the influence on system response from non-linear factors, and considers based on NF by preserving second-order equation. Then put forward a non-linear interactive index to evaluate the intensity of interaction among SVC, SVC and TCSC, and UPFC. In the cases of study of multi-machine power system, the effectiveness of NF analytical method was verified through theoretical analysis and time-domain simulation.

5.2.2 Analytical method of relative gain array

Relative Gain Array (RGA), put forward by Bristol in 1996, is an effective method of analyzing the interaction of multi-variable control system. Also, it is a widely used designing tool of controlling system [8]. As for multi-variable control system, RGA is a method of providing optimal combination of control variable and controlled variable by observing the interaction among each input and output variables. It can also provide interaction messages among different control processes. Therefore, RGA is widely used now. Reference [9] studied the possibility of the application of RGA in static analysis of power system. It compared traditional residue, characteristic root and factor analysis method, indentified and studied the problem of site selection of PSS. Reference [10] studied the possibility of designing damping FACTS controller by improving RGA.

5.2.3 Singular value decomposition method

Singular Value Decomposition (SVD) Method is an important method of analyzing the interaction of input and output variables of system [11]. When apply SVD in a frequency range, the main point is, as opposed to original vector, singular vector decreases little, and the interaction of control circuit is small. The advantage of SVD is capable of dealing with time-lag system and non-positive-order system. But when the singular values are too close, SVD will be very sensitive or even unreliable.

5.2.4 NI method

NI method, put forward by Niederlin ski in 1971, is a controller matching method [12]. NI method is widely used in the choice of variable matching of control system just like RGA. Both methods are easy, and they can indicate the degree of coupling of control circuit only depend on object model. The standard of NI method based on variable matching was introduced in reference [13]. In reference [13], it said that NI value is an indicator of global interaction. And it can solve the problem of the choice of variable matching. Reference [14] and [15] put forward the combination of RGA and NI method. But commonly NI indicator is served as a tool of RGA, when analyze the interaction and pairing pattern among controllers. Use RGA to pair, then check if the system stable through NI method.

5.2.5 Analytical method of interaction based on gramian

Gramian is built on dynamic model of state space of system. It can describe the controllability and observability of one stable system, and it suits for continuous or discrete system. Take Gramian of system as quantitative analytical way to describe the signal of input and output as well as the controllability and observability of system [16]. Reference [17] took Gramian as representation of information content, combined with Homology group and information

content, put forward an optimum distribution of rotor angle measurement device. Gramian is model based on state space of system, but when a system is represented by four matrixes (A, B, C, D), if feedback matrix of D exists, this method is not applicable.

5.2.6 The standard of Eigen value of Jacobian determinant

The standard of Eigen value of Jacobian Determinant, put forward based on difficulty analysis of calculating inverse matrix of steady state gain matrix G, can be used to guide variables pairing. Best match of variables can make single circuit independent. They are matches that off-diagonal elements of G have least inverse matrix effect on G. For a system that doesn't have interaction, inverse matrix of G is equal to the inverse of a matrix consisted of diagonal elements.

From Reference [18] and [19], we knew that when the inverse of G G_{21} is represented by Jacobian and diagonal matrix, the necessary and sufficient condition of converging G_{21} is that the value of max eigen value of Jacobian matrix must be less than 1. Therefore, the value of eigen value is the least among all possible pairings get from Jacobian matrix. But the difficulty of applying this method is that there are many pairings needed detecting, and the off-diagonal elements of G have significant influence on the process of inversing. So this method doesn't apply to predict pairing.

5.2.7 RHP zero method

RHP zero method can be used to guide variables pairing. Considering pairing different outputs and inputs, system would have different zeros. On some conditions, RHP zero exists. These zeros would make the control performance of closed-loop worse, which we should try to avoid when pairing controller.

From reference [12], we can get that zero would not change with feedback control, but the pole would change with feedback control. As the feedback control gain decreases, the pole of closed-loop would move to the position of the pole of open-loop. And it is going to make closed-loop system unstable possibly. Therefore, the principle of choosing pairing output and input is let closed-loop have least RHP zeros. Especially, we should avoid there are RHP zeros in the frequency region considered.

6. Coordinated control of interaction

Theoretically, the most effective method of solving the problem of interaction among FACTS controllers is to apply multi-variable coordinated control. Because a MIMO system is consisted of a flexible AC transmission system that has many control function (may be many FACTS devices), so a MIMO is the easiest method of solving the problem of interaction among controllers and the stability of closed-loop system. However, because of the complexity of multi-variable control, actually it's difficult to apply it in power system. Usually, we use coordinated control to solve the problem of the interaction among controllers.

6.1 Coordinated control of multi-objective of single FACTS

FACTS has many functions. Generally, controllers are designated aiming for different functions respectively. It makes every control function isolated or even contradicted, so it's

time to consider the coordinated control among multiple targets. Reference [21] pointed out that STATCOM which has static parameters couldn't have both satisfying voltage control accuracy and damping control effect. In order to achieve the coordination between two targets, controller based on rules was designated. It means defining the structure and parameters of controller according to the operating condition.

Reference [22] introduced a new control method of multi-objective of FACTS. That is an intelligent control method of FACTS device. This method combined with the advantages of predictive control and inverse system control. The process of the signal of optimal control of FACTS has two sub-processes. First, filter the candidate outputs of FACTS device, and get the best output. Second, inversed calculate the actual control signal of FACTS device according to the best output. In every sub-process, Artificial Nervous Network Technique (ANNT) and fuzzy reasoning are used to solve different problems. Reference [22] took Advenced Static Var Generator (ASVG) as an example to introduce designation steps of intelligent predictive controller based on the method of intelligent predictive. Electromechanical simulation example proved the effectiveness of this new control method.

6.2 The theory of multi-objective evolution

In real world, most optimum problems are relative to multiple targets. Those targets are not alone. They are usually coupling and competing. Each target has different meanings and dimensions. The complexity and competitiveness would make optimization difficult [23].

The optimal solution of single target has clear definition, however, the definition couldn't promote to multiple targets. It's different from the definition of single target that multi-objective problem doesn't have global optimal solution, but it has a collection of global optimal solution. The optimal solution of multi-objective problem is called collection of global optimal solution, and the elements of it incomparable for global target.

Commonly multi-objective problem can be described as[227]:

$$\min/\max\{f_m(x)\}, m = 1, 2, \cdots, m;$$
$$\text{subjct to } g_j(x) \geq 0, j = 1, 2, \cdots, J;$$
$$h_k(x) = 0, k = 1, 2, \cdots, K$$

Among, decision vector: $x \in R^n$, target vector $f(x) \in R^n$, and $g_i(x)$ and $h_k(x)$ are inequality and restrain condition of equation respectively.

The essence of multi-objective is finding a group of decision vector which is meeting the demand of restraint condition so as to make target vector be the maximum or minimum at feasible region. It's different from optimal problem of single target that it's almost impossible that all target functions are maximum or minimum. Therefore, people put forward the concept of optimal solution of Pareto.

6.3 ZMOEA method

Revolution algorithm based on population can implicit parallel search for multiple solutions in solution space, and it can also improve the efficiency of calculating through similarity of different solution. The combination of revolution algorithm and the concept of optimal

Pareto can produce real revolution algorithm based on the concept of optimal Pareto so as to search for the non-inferiority optimal solutions.

Using revolution algorithm to solve multi-objective problem is like traditional algorithms. Objective function must be scalarized. Fitness, served as the assessed value of individual of next generation, must be scalarized. The process of scalarization should monotonic transformation of coordinate of objective function so as to let the individual endow the best fitness of Pareto. This transformation isn't the only one. It concludes of the preference information of designer when he is assessing individual. Generally, if one scalared fitness is achieving, revolution algorithms use common selection method to progress [24]. There are 3 kinds of revolution algorithms to solve the multi-objective problem [25].

Quantitative method: Multiple targets usually convert to single one so as to optimize them. This kind of method includes weighted method, minimax method, and objective vector method and so on. These methods are usually the same as single target optimum method.

Non-Pareto method based on population: Different objective functions have effect on choice of different individuals of population in turns. The method that the different individuals of population are sorted according to every objective function belongs to non-Pareto method based on population.

Sorting method based on Pareto: Sorting population directly according to Pareto.

6.4 Steps of multi-objective evolution

Steps of Multi-Objective evolution are as follows.

a. Decompress a group which has N chromosomes initially. Coding chromosomes in floating mode.
b. Decoding chromosomes and transferring it to real value of parameter region of controller optimized. Then substitute it into equation unknown. Sorting target values in Pareto way. Then calculating the initial fitness value.
c. Choosing and copying, then producing new population. According to the difference among fitness values, choosing in the way of roulette, and generating new population.
d. Crossover the individuals of new population, and mutate them. Increase the diversity of population. Interleaved mode adopts single-point crossover. And mutation can prevent algorithm from being optimum partially to some extent.
e. Operating Elitism [26], and combining the population produced above with old population. Sorting them, and generating a new population.
f. After evolution of one generation and producing next generation, go back to step B until it meet the termination conditions. Find out some optimum point of Pareto or the some close to it.

Termination conditions can be maxgenterm, or we can choose other indicators to judge restraint condition.

6.5 Multi-objective optimal design of TCSC and SVC

Among evolutionary algorithms, fitness function decides the evolutionary direction of population. In order to transfer coordination problem to multi-objective optimal design

problem, we should choose a function consisted a series of performance index of system response. Choose control objectives of TCSC and SVC, it means active power of the line, signal of node voltage supported by SVC, and variance integral of reference value set by controller to be performance index. As mentioned above, the problem of multi-objective optimal design of TCSC and SVC can be described as:

$$\min \begin{cases} F_V(K_P, K_I, K_A) = \int_0^{t_s} |\Delta V_{SVC}| \, dt \\ F_V(K_P, K_I, K_A) = \int_0^{t_s} |\Delta P_{TCSC}| \, dt \end{cases}$$

Constrain condition of optimized parameters is:

$$0 \leq K_P \leq 30;$$
$$0 \leq K_I \leq 30;$$
$$0 \leq K_{SVC} \leq 150.$$

Where K_P is scale factor of TCSC PI controller, K_I is double integral TCSC PI controller, and K_{svc} is the gain factor of SVC voltage regulator.

6.6 The coordinate control case of TCSC and SVC

As figure 7 shows, install TCSC and SVC in system. TCSC is installed on supply arms. The purpose of installing TCSC is to control active power of line by changing the reactance of line. SVC is installed on bus bar in parallel. The purpose of installing SVC is to make the voltage of installation point stable. Adopt multi-objective evolution algorithm to optimize 3 parameters of both controllers of FACTS

Let the population size be 50, let maximum optimum algebra be 50, let crossover frequency be 0.8, and let mutation rate be 0.07. Figure 10 is convergence rate curve of MOEA, and figure 11 is non-optimal Pareto solution. It can be seen from figure 10. The progress ratio of MOEA is relatively high initially. After evolution, the progress ratio gradually tends to zero. It means population is close to Pareto optimal solution. As for Pareto optimal solution described by figure 11, according to the definition of Multi-Objective problem, first, the non-optimum solution is a solution in feasible region. Second, when comparing any solution with other feasible solutions of non-optimal solution, at least one object is better than other feasible solution. Table 1 shows partial Pareto solution.

Group	K_P	K_I	K_{SVC}
1	0.9456774	11.61006	81.08093
2	0.9456834	13.04966	83.08023
3	0.9366024	5.395905	103.3966
4	0.6860377	6.610057	58.17931
5	1.00992	6.395556	49.3839
6	0.4875605	28.76538	112.8552

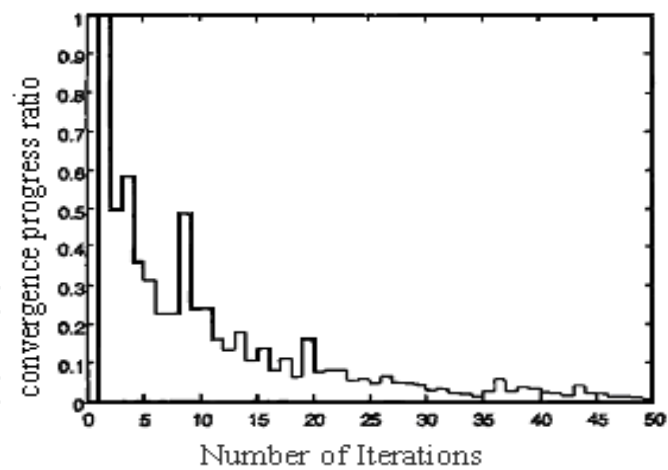Table 1. Partial Pareto optimal solution

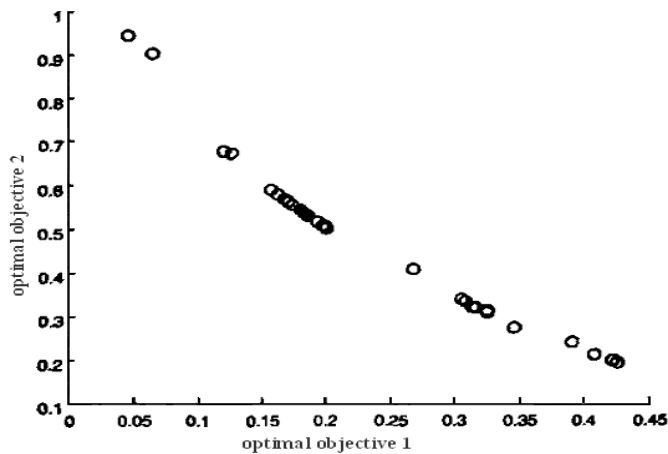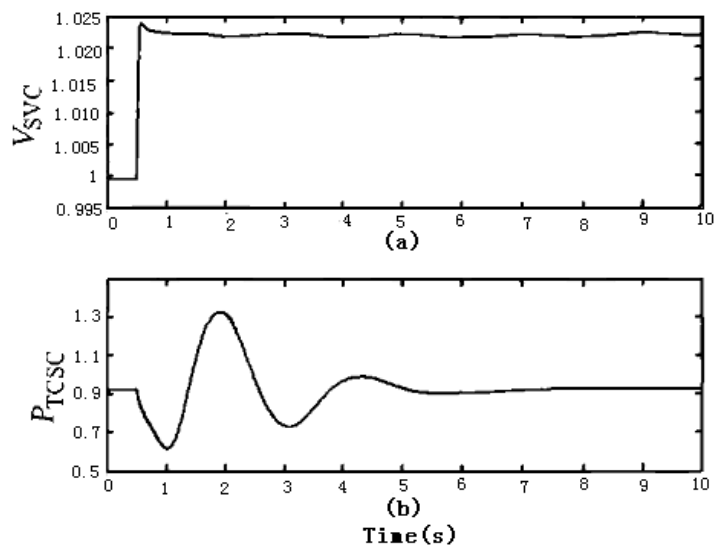Fig. 10. Progress ratio of multi-objective evolution progress

Fig. 11. Pareto-optimal front for two-objective design

(a) Order step response curve of SVC when TCSC is closed.
(b) Changing curve of an Active power controlled by TCSC when voltage node of SVC steps

Fig. 12. Combined-operation performance of SVC with TCSC

As you can see in figure 12, the coordinate design of TCSC and SVC is successful, and the difference between different groups of parameters of Pareto solution set is: one group of optimal solution has better control effect on TCSC and worse effect on the stability of voltage of SVC. The purpose of Multi-Objective coordinate designation is to analyze which control object is more important according to actual operation when the different objects of SVC and TCSC interact each other, and lead to the worst situation that both objects couldn't be optimum. Then choose a group of optimal solution among Pareto solution to solve the problem of coordinate operation after installing SVC and TCSC.

Now analyze the problem of coordinate control considering the least energy consumption.

The impedance of single-phase traction transformer $R_T + jX_T$ can be calculated by short circuit voltage $U_d\%$, short circuit power loss ΔP_C with reduction to 27.5kV side.

$$R_T = \frac{\Delta P_C U_N^2}{1000 S_N}(\Omega),$$

$$X_T = \frac{U_d\% U_N^2}{100 S_N}(\Omega),$$

U_N=27.5KV, and S_N is the rated capacity of traction transformer. We can get the voltage loss of transformer winding through transformer impedance $R_T + jX_T$

$$\Delta U = (R_T \cos\Phi_2 + X_T \sin\Phi_2)(I_a + I_b),$$

I_a and I_b are currents of both supply arms.

Active power losses of traction transformer are iron loss ΔP_0 and copper loss. The iron loss is no-load loss, which is fixed, and has nothing to do with current flows through load. ΔP_0 can be calculated by copper loss, which is called load loss or changeable loss, and changing with current flows through load. Active power loss of single-phase is:

$$\Delta P = I^2 R_T$$

According to the principle of reasonably utilize the place and the analysis above, assume installing TSC and series compensation which are on 30-meter supply arm on the place at the distance of 8km from transformer, and use l and s to represent the distances of two sections. The high-voltage side and low-voltage side of transformer are 100kV and 27.5kV. Assume the capacitors of SVC and TCSC are X_{C1}, and X_{C2}. X_{C1} is a continuous variable, and X_{C2} is a undetermined variable. The energy consumption function of entire system is:

$$P(X_{C1}, X_{C2}) = (X_{C1} + X_{C2})tg\alpha + \int_0^s I_q[U_1 - \rho Ix]dx$$

$$+ \int_s^l I_q[U_1 - \rho Is + I_q X_{C2}\sin\Phi_1 - \rho I_q(x-s)]dx + I^2 R_T$$

$$Q(X_{C1}, X_{C2}) = U_1 I\sin\Phi_2 + U_2 Iq\sin\Phi_2 + (k-1) U_1^2 \div X_T - I_q^2 X_{C2}\sin\Phi_2$$

From equation (13) and (14), we can get the objective function of system is:

$$W = \min\{P^2(X_{C1}, X_{C2}) + Q^2(X_{C1}, X_{C2})\}^{0.5}$$

The functions of restrain condition are：

$$U_1 \le 30\text{kV};$$
$$U_3 \ge 20\text{kV};$$
$$\cos\Phi_2 > 0.9_。$$

Let's discuss the minimum value of W. Because W and W^2 are the least, in order to discuss easily, we use the minimum value of W^2 to take the place of W, then,

$$U_1 = U_S - (R_T\cos\Phi_2 + X_T\sin\Phi_2)I,$$

$$U_2 = U_1 - (\gamma_1\cos\Phi_2 + X_1\sin\Phi_2)I = U_S - [(R_T + \gamma_1)\cos\Phi_2 + (X_T + X_1)\sin\Phi_2]I_。$$

At the same time, from the equation below,

$$\frac{I_C}{\sin(\Phi_1 - \Phi_2)} = \frac{I_q}{\sin(\pi/2 + \Phi_2)}$$

$$\frac{I}{\sin(\pi/2 - \Phi_1)} = \frac{I_q}{\sin(\pi/2 + \Phi_2)}$$

we can get,

$$I_C = I_q \frac{\sin(\Phi_1 - \Phi_2)}{\cos\Phi_2}$$

$$I = I_q \frac{\cos\Phi_1}{\cos\Phi_2}$$

From $I_C = U_2 \div X_C$ and $I_C = I_q\sin\Phi_1 - I\sin\Phi_2$, we can get,

$$U_2 = (I_q\sin\Phi_1 - I\sin\Phi_2) \times X_C = I_q X_C (\sin\Phi_1 - tg\Phi_2\cos\Phi_1)$$

$$U_1 = U_S - I_q (R_T + X_T\, tg\Phi_2)\cos\Phi_1$$

then,

$$U_S - I_q [(R_T + \gamma_1) + (X_T + X_1)tg\Phi_2]\cos\Phi_1 = I_q X_C (\sin\Phi_1 - tg\Phi_2\cos\Phi_1)$$

We can get from the equation above,

$$tg\Phi_2 = \frac{U_S - I_q[(R_T + \gamma_1)\cos\Phi_1 + X_C\sin\Phi_1]}{(X_T + X_1 - X_C)I_q\cos\Phi_1}$$

or

$$X_C = \frac{U_S - I_q[(R_T + \gamma_1) + (X_T + X_1)tg\Phi_2]\cos\Phi_1}{I_q(\sin\Phi_1 - tg\Phi_2\cos\Phi_1)}$$

In order to get the best compensation value of capacitor, find partial derivative of W^2,

$$\frac{\partial W^2}{\partial X_{C1}} = 2P(X_{C1}, X_{C2})\{tg\alpha + \int_0^s I_q[\frac{dU_1}{dX_{C1}} - \rho x\frac{dI}{dX_{C1}}]dx$$

$$+ \int_0^s I_q[\frac{dU_1}{dX_{C1}} - \rho(x-s)\frac{dI}{dX_{C1}}]dx + 2IR_T\frac{dI}{dX_{C1}}\}$$

$$+2Q(X_{C1}, X_{C2})\{I_q\cos\Phi_1 tg\Phi_2\frac{dU_1}{dX_{C1}} + U_1 I_q\cos\Phi_1\frac{dtg\Phi_2}{dX_{C1}} + I_q\sin\Phi_2\frac{dU_2}{dX_{C1}}\}$$

$$+(U_2 I_q - I_q^2 X_{C2})\cos\Phi_2\frac{d\Phi_2}{dX_{C1}}$$

$$\frac{\partial W^2}{\partial X_{C2}} = 2P(X_{C1}, X_{C2})\{tg\alpha + I_q\sin\Phi_1(l-s)\} - 2Q(X_{C1}, X_{C2})I_q^2\sin\Phi_2$$

$$\begin{cases} \dfrac{\partial W^2}{\partial X_{C1}} = 0 \\ \dfrac{\partial W^2}{\partial X_{C2}} = 0 \end{cases}$$

Calculate the equations above, and we can get the best compensation value $\{X_{C1}^*, X_{C2}^*\}$ which cause least energy cost.

In conclusion, the capacity of compensator with parallel capacitor XC1 is decided by U_2, and the capacity of TCSC is decided by X_{C2}. In return, after installing TCSC, the voltage drop caused by it subtracts the voltage drop caused by inductance of contact system. It could be considered that capacitor subtracts inductance. Because the voltage drop of supply arms caused by TCSC and the voltage drop caused by inductance cancel out, the voltage loss of system reduces obviously, and the power factor improves a lot.

Adopting TCSC and optimally distributing the capacity of SVC and TCSC according to the real-time condition of electric traction can not only save power, improve the power quality of Traction Power Supply system, but also protect the equipments, increase the safety of operation of trains. Solving the problem of coordinately control the electric traction reasonably is meaningful for the development of Traction Power Supply system.

7. References

[1] Huang Yuanliang, QIAN Qing-quan. Research on improving quality of electricity energy in train's traction[J], Control and Decision, 2010, 25(10): 1575-1579(in Chinese).
[2] Cao Yi-jia *et al*. Research Progress on Interaction and Coordinated Control Among FACTS Controllers [J], Proceedings of the CSU-EPSA: 2008 20(1): 1~8.(in Chinese)
[3] Larsen E V, Sanchez2Gasca J J , Chow J H. Concepts for design of FACTS controllers to damp power swings[J]. IEEE Transon Power System s, 1995, 10(2): 948~956.
[4] Thapar J, VittalV, Kliemann, *et al*. Application of the normal form of vector fields to predict interarea separation in power system s [J]. IEEE Transon Power Systems, 1997, 12 (2): 844- 850.

[5] Li Yinghui, Zhang Baohui. A new method to determine the transient stability boundary using nonlinear theory [J]. Proceedings of the CSEE, 2000, 20 (1): 41- 44.

[6] Zou Z Y, J iang Q Y, Cao Y J , *et al* . Application of the normal forms to analyze the interact ions among the multi-control channels of UPFC [J]. International Journal of Electrical Power and Energy System s, 2005, 27 (8): 584- 593.

[7] Zou Z Y, J iang Q Y, Cao Y J, *et al*. Normal form analysis of the interact ions among multiple SVC controllers in power system s [J]. IEE Proceedings-Generation, Transmission and Distribution, 2005, 152 (4) : 469- 474.

[8] B risto l E H. O n a new measure of interact ion for multivariable process control [J]. IEEE Trans on Automatic Control, 1966, 11 (1): 133- 134.

[9] M ilanovic J V, Duque A C S. Identification of electromechanical modes and placement of PSS susing relative gain array [J]. IEEE Transon Power Systems, 2004, 19 (1): 410- 417.

[10] Zhang Pengxiang, *et al*. Application of relative gain array method to analyze interact ion of multi-fuctional facts controllers [J]. Proceedings of the CSEE, 2004, 24 (7): 13- 17.

[11] Hamdan A M A. A n invest igat ion of the significance of singular value decomposition in power system dynamics [J]. International Journal of Electrical Power and Energy System s, 1999, 21 (6): 417- 424.

[12] Niederlinski A. A heuristic app roach to the design of linear multivariable interacting control systems [J]. Automatica, 1971, 7(6): 691-701.

[13] Zhu Z X, Jutan A. A new variable pairing criterion based on the Niederlinski index [J]. Chemical Engineering Communications, 1993, 121 (18): 235-250.

[14] Yu C C, L uyben W L. Robustness with respect to integral controllability [J]. Industrial and Engineering Chemistry Research, 1987, 26 (5): 1043-1045.

[15] Zhu Z X, Jutan A. Stability robustness for decentralized control systems [J]. Chemical Engineering Science, 1993, 48 (13) : 2337- 2343.

[16] Conley A, Salgado M E. Gramian based interaction measure [C] ‖ P roceeding of the 39th IEEE Conference on Decision and Control, Sydney, NSW, Australia: 2000.

[17] Chu Xiaodong,Liu Yutian. Optimal placement of rotor angle transducers[J]. Proceedings of the CSEE, 2003, 23 (9): 132- 136.

[18] M ijares G, Co le J D, Naugle N W, *et al*. A new criterion for the pairing of control and manipulated variables [J]. A IChE Journal, 1986, 32(9): 1439-1449.

[19] Schm idt H, Jacobsen E W. Selecting control configurations for performance with independent design [J]. Computers and Chemical Engineering, 2003, 27 (1): 101- 109.

[20] Farsangi M M , Song Y H, Lee K Y. Choice of FACTS device control inputs for damping interarea oscillations [J]. IEEE Trans Power System s, 2004, 19 (2) : 1135- 1143.

[21] Li Chun, Jiang Qirong, Wang Zhonghong. Design of a rule based controller for STA TCOM [J]. Proceedings of the CSEE, 1999, 19 (6): 56- 60.

[22] Lu Qiang, *et al*). Target oriented intelligent predictive evaluating control method for FACTS devices (PART 1) [J]. Power System Techno logy, 1998, 22 (4): 6- 9, 12.

[23] K. Deb. Multi-Objectiveive Optimization using Evolutionary Algorithms. N Y: John Wiley & Sons. I nc.

[24] D. Cvetkovic, I. C. Parmee. Preferences and Their Application in Evolutionary Multi-Objectiveive Optimization. IEEE Transactions on Evolutionary Computation, 2002, 6(1): 42 -57.

[25] C. M. Fonseca, P. J. Fleming, An Overview of Evolutionary Algorithms in Multi objective Optimization. Evolutionary Computation, 1995, 3(1): 1-16

[26] P. Ju, E. Handschin, F. Reyer. Genetic algorithm aided controller design with application to SVC. IEE Proceedings of Generation, Transmission and Distribution, 1996, 143 (3): 2 58-262.
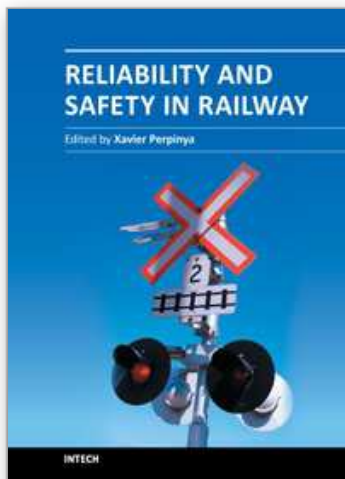
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Edited by Dr. Xavier Perpinya

In railway applications, performance studies are fundamental to increase the lifetime of railway systems. One of their main goals is verifying whether their working conditions are reliable and safety. This task not only takes into account the analysis of the whole traction chain, but also requires ensuring that the railway infrastructure is properly working. Therefore, several tests for detecting any dysfunctions on their proper operation have been developed. This book covers this topic, introducing the reader to railway traction fundamentals, providing some ideas on safety and reliability issues, and experimental approaches to detect any of these dysfunctions. The objective of the book is to serve as a valuable reference for students, educators, scientists, faculty members, researchers, and engineers.

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