SVC Control System Based on Instantaneous Reactive Power Theory and Fuzzy PID

Juanjuan Wang, Chuang Fu, and Yao Zhang

***Abstract*—Industrial static var compensators (SVCs) are typically applied at or near the load center to mitigate voltage fluctuations, flicker, phase unbalance, or other load-related disturbances. In this paper, a phase-to-phase "open + close" control scheme for industrial SVC is proposed. The forward loop is to guarantee short response time, while the feedback loop is to ensure good dynamics and steady characteristics of SVC. The fast compensation algorithm for asymmetric industrial loads based on instantaneous reactive power theory is used in the forward loop, while a fuzzy proportional–integral–differential control strategy is applied to the close loop. The hardware and software of this SVC control system is developed based on SIMATIC-TDC and WinCC; the former is the most modern but well-proven industrial controller, while the latter is the globally used human machine interface system. Many industrial applications show that this kind of control system can meet the strict performance and reliability requirements of industrial SVCs.**

***Index Terms*—Control system, fuzzy proportional–integral–differential (PID), instantaneous reactive power theory, SIMATIC-TDC, static var compensator (SVC), WinCC.**

I. Introduction

With the development of China's economy, the incompatibility between consumption demand and the capacity of the power system has become more serious. On the one hand, many kinds of disturbing industrial loads, which have the characteristics of nonlinearity, asymmetry and imbalance, bring forth problems of power quality such as harmonics, voltage fluctuation and flicker, three-phase voltage imbalance and poor power factor. On the other hand, more types of equipment are sensitive to power quality. Customers need high quality electric energy with the attributes of high reliability, high transient stability and high controllability [1]–[4]. Although the active power filter and static synchronous compensator (STATCOM) have been studied in depth and put into practical use [4]–[9], they are still too expensive for customers. The static var compensator (SVC), which uses conventional thyristor-phase-controlled technology to change the generation or absorption of reactive power rapidly, is still an efficient and economical method to solve the aforementioned problems [10]–[14].

The primary purpose of managing an industrial SVC is to control system reactive power in response to measured system variables, auxiliary inputs for supplementary control, or operator inputs as soon as possible. The dynamic performance of such SVCs mostly depends on the response time of the control system. In this paper, a phase-to-phase "open + close" control strategy for industrial SVCs is proposed. The forward loop is to guarantee short response time, while the feedback loop is to ensure good dynamics and steady characteristics of SVCs. The fast compensation algorithm for asymmetric industrial loads based on instantaneous reactive power theory is used in the forward loop, while a fuzzy proportional–integral–differential (PID) control strategy is applied to the closed loop. To simplify development work and guarantee the reliability of equipment, the hardware and software of this SVC control system is developed based on SIMATIC-TDC and WinCC. The former is the most modern but well-proven industrial controller, while the latter is the globally used human machine interface (HMI) system.

The SVC control system proposed in this paper has been applied to many SVC projects in China such as the 220-kV substations of Shougang Steel-Plate Company, Tianjin Light-rail Transport Company and Bombardier Power Transportation Company.

II. Compensation Algorithm of Asymmetric Loads Based on Instantaneous Reactive Power Theory

The traditional definition of reactive power cannot meet the requirements for fast response of industrial SVCs [14], [15]. The instantaneous reactive power theory [16]–[21] provides an effective method for the real-time measurement of instantaneous reactive power. Through $\alpha-\beta$ transformation, the three-phase currents and voltages are converted into variables expressed by 2-D vectors. The instantaneous real power and instantaneous reactive power are represented by the dot product and the cross product of α and β components [16]–[18], respectively. The instantaneous power thus becomes a 1-D vector with positive and negative variables, which is convenient for engineering applications.

SVC is a kind of shunt compensation installation, which usually consists of shunt filters and reactors whose capacity can be adjusted dynamically. The control system regulates the output of equivalent susceptance by adjusting the delay firing angles of thyristors. Thus, the load reactive power can be compensated in real time.

Orthogonal transform is valid not only to steady-state phasors but also to instantaneous variables [16]–[18]. Suppose the system voltage is ideal sinusoidal, which can meet requirements of most engineering applications. By using the symmetrical

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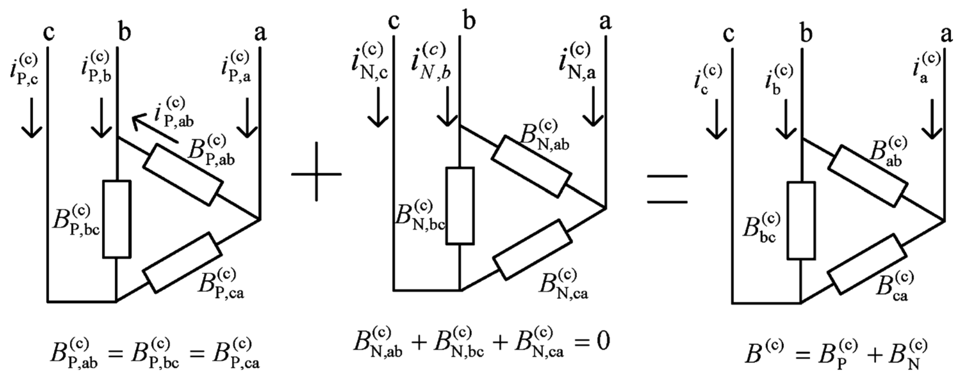


Fig. 1. Equivalent pattern of compensation equipment.

component transfer method, the SVC can be divided into two equivalent parts: a fundamental frequency positive sequence compensation network with balanced three-phase susceptances, which only produce fundamental frequency positive sequence currents to provide reactive currents; and a fundamental frequency negative sequence compensation network with unbalanced three-phase susceptances, which only produce fundamental frequency negative sequence currents to offset the fundamental frequency negative currents produced by unbalanced loads. Fig. 1 shows the equivalent network of compensation equipment.

Suppose the power grid voltage is ideal sinusoidal [21]. A-phase voltage is appointed as the reference voltage. The busbar voltage could be expressed as

$$\begin{cases} u_{\mathrm{a}} = \sqrt{2}U\cos\omega t \\ u_{\mathrm{b}} = \sqrt{2}U\cos(\omega t - 2\pi/3) \\ u_{\mathrm{c}} = \sqrt{2}U\cos(\omega t + 2\pi/3) \end{cases} \tag{1}$$

where U is the effective value of system phase voltage and ω is the angular frequency of the voltage.

At the same time, the load current may be represented as follows:

$$\begin{cases} i_{\mathrm{a}} = \sqrt{2}\sum\limits_{n=1}^{\infty}\left[I_{1n}\cos(n\omega t + \varphi_{1n}) + I_{2n}\cos(n\omega t + \varphi_{2n})\right] \\ i_{\mathrm{b}} = \sqrt{2}\sum\limits_{n=1}^{\infty}\left[I_{1n}\cos(n\omega t + \varphi_{1n} - 2\pi/3)\right. \\ \qquad\qquad \left. + I_{2n}\cos(n\omega t + \varphi_{2n} + 2\pi/3)\right] \\ i_{\mathrm{c}} = \sqrt{2}\sum\limits_{n=1}^{\infty}\left[I_{1n}\cos(n\omega t + \varphi_{1n} + 2\pi/3)\right. \\ \qquad\qquad \left. + I_{2n}\cos(n\omega t + \varphi_{2n} - 2\pi/3)\right]. \end{cases} \tag{2}$$

According to Fig. 1 and circuit principles, the compensation susceptance network based on instantaneous reactive power can be deduced as follows:

$$\begin{cases} UB^{(c)}_{\mathrm{N,ab}} = -\frac{1}{3}i_{1f}\sin\varphi_{1f} + \frac{1}{\sqrt{3}}I_{2f}\cos\varphi_{2f} - \frac{1}{3}I_{2f}\sin\varphi_{2f} \\ UB^{(c)}_{\mathrm{N,bc}} = -\frac{1}{3}i_{1f}\sin\varphi_{1f} + \frac{2}{3}I_{2f}\sin\varphi_{2f} \\ UB^{(c)}_{\mathrm{N,ca}} = -\frac{1}{3}i_{1f}\sin\varphi_{1f} - \frac{1}{\sqrt{3}}I_{2f}\cos\varphi_{2f} - \frac{1}{3}I_{2f}\sin\varphi_{2f} \end{cases} \tag{3}$$

where I_{1f} is the effective value of load fundamental frequency positive sequence current, I_{2f} is the effective value of load fundamental frequency negative sequence current, φ_{1f} is the phase angle of load fundamental frequency positive sequence current, φ_{2f} is the phase angle of load fundamental frequency negative sequence current, $B^{(c)}_{\mathrm{N,ab}}$ is the load AB phase-to-phase compensation susceptance, $B^{(c)}_{\mathrm{N,bc}}$ is the load BC phase-to-phase compensation susceptance, and $B^{(c)}_{\mathrm{N,ca}}$ is the load CA phase-to-phase compensation susceptance.

Definitions: p_{1f} is the load fundamental frequency positive sequence instantaneous active power, q_{1f} is the load fundamental frequency positive sequence instantaneous reactive power, p_{2f} is the load fundamental frequency negative sequence instantaneous active power, and q_{2f} is the load fundamental frequency negative sequence instantaneous reactive power.

According to (3), the compensation network can also be expressed by the above defined instantaneous active and reactive powers as

$$\begin{cases} (\sqrt{3}U)^2 B^{(c)}_{\mathrm{N,ab}} = \frac{1}{3}q_{1f} + \frac{1}{\sqrt{3}}P_{2f} + \frac{1}{3}q_{2f} \\ (\sqrt{3}U)^2 B^{(c)}_{\mathrm{N,bc}} = \frac{1}{3}q_{1f} - \frac{2}{3}q_{2f} \\ (\sqrt{3}U)^2 B^{(c)}_{\mathrm{N,ca}} = \frac{1}{3}q_{1f} - \frac{1}{\sqrt{3}}P_{2f} + \frac{1}{3}q_{2f}. \end{cases} \tag{4}$$

In (3) and (4), the first item is the compensation susceptance of positive sequence network; the latter two items are the compensation susceptance of negative-sequence network.

Using the A-phase voltage as the reference, according to (1) and (2), the positive-sequence fundamental frequency power can be gained through coordinate transformations and using low-pass filters

$$\begin{bmatrix} p_{1f} \\ q_{1f} \end{bmatrix} = \begin{bmatrix} 3U_{1f}I_{1f}\cos(-\varphi_{2f}) \\ 3U_{1f}I_{1f}\sin(-\varphi_{2f}) \end{bmatrix}. \tag{5}$$

In a similar way, using the negative sequence synchronous rotary coordinate axis as the reference frame, the fundamental frequency negative-sequence power can be calculated

$$\begin{bmatrix} p_{2f} \\ q_{2f} \end{bmatrix} = \begin{bmatrix} 3U_{1f}I_{2f}\cos(-\varphi_{2f}) \\ 3U_{1f}I_{2f}\sin(-\varphi_{2f}) \end{bmatrix}. \tag{6}$$

According to (5) and (6) above, the fundamental frequency positive-sequence power and negative-sequence power can be calculated, then the compensation susceptances can be gained.

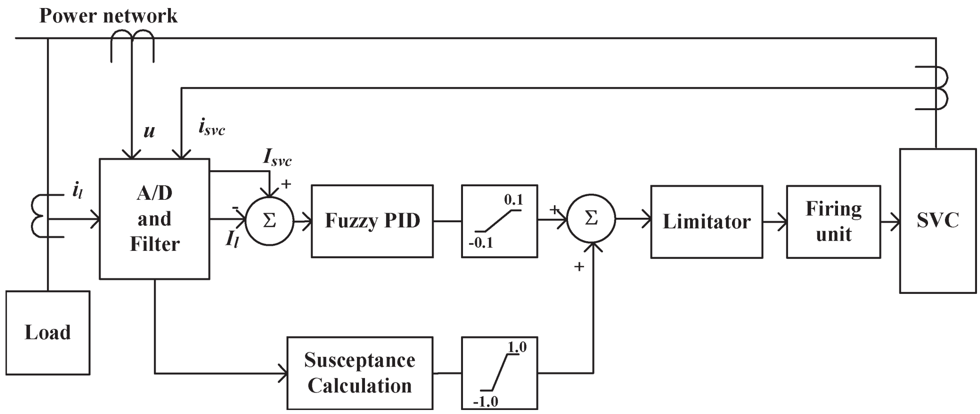


Fig. 2. Control principle of load compensation SVC.

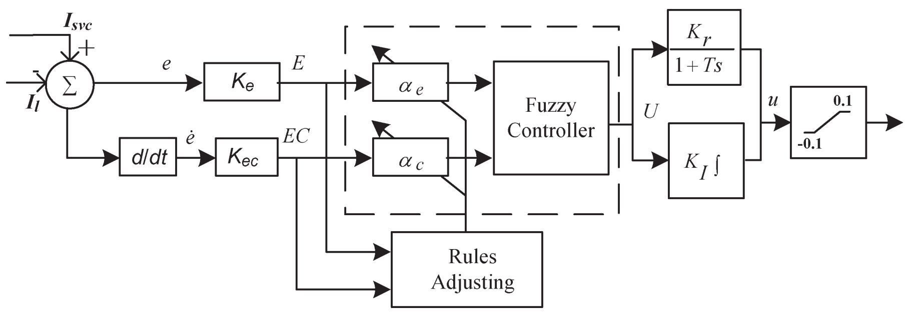


Fig. 3. Structure of adaptive nonlinear analytical fuzzy controller.

III. Design of the SVC Control System

To acquire excellent dynamic and static performance, the SVC control system equipped with two parallel control loops is proposed. One is an open-loop fast load balancing and reactive power control scheme, while the other is a phase-to-phase closed-loop reactive current control scheme. The open-loop scheme uses load compensation arithmetic based on instantaneous reactive power theory proposed in the above section. Fuzzy PID, which has generated significant interest in various applications and has been introduced in the power system and power-electronics field [21]–[25], is applied to the phase-to-phase closed-loop scheme. The regulated ranges are different for the open-loop and closed-loop. For different purposes, the variables of the closed-loop control may be reactive power, reactive current or power factor. Fig. 2 shows the control principle of the SVC control system with the reactive current close-loop.

In Fig. 2, the unit of "Susceptance Calculation" is the open-loop scheme, while fuzzy PID is the closed-loop scheme. The close-loop is made up of three fuzzy PID controllers, with the PID parameters dynamically tuned by the fuzzy logic module. The outputs of the fuzzy PID controller are added to the outputs of the forward loop; these sums are the individual phase-to-phase compensation susceptances of the SVCs. The regulated range of the open-loop is between -100% and 100% of the thyristor controlled reactor (TCR) rated susceptance, while the regulated range of the closed-loop is between -10% and 10%. Thus, fast response, good dynamics and steady characteristics can be guaranteed.

The more detailed diagram of the fuzzy PID controller is given in Fig. 3. The error and the error-changing rate are obtained by comparing the SVC individual phase-to-phase reactive power with the load individual phase-to-phase reactive power.

The control rule in the fuzzy controller with adjustable factor is given below

$$U = [\alpha E + (1-\alpha)EC], \qquad \alpha \in (0,1) \tag{7}$$

where the control output is determined by input E (deviation) and EC (change rate of the deviation), and α is a weight factor of E (or EC). The different control rules are produced from different α (α_e and α_c). The following formula is introduced to define the parameter α:

$$\alpha = \frac{1}{N}(\alpha_s - \alpha_0)|E| + \alpha_0 \tag{8}$$

where N is fuzzy numbers that denote the error linguistic labels in fuzzy sets, and $0 \leq \alpha_0 \leq \alpha_s \leq 1, \alpha \in [\alpha_0, \alpha_s]$.

The fuzzy controller is established as follows:

$$U = U_{\max} \frac{1-e^{-x}}{1+e^{-x}} \tag{9}$$

where

$$x = \alpha_\mathrm{e} E + \alpha_\mathrm{c} EC. \tag{10}$$

The one-order inertia component in the proportional output unit is used to eliminate high-frequency disturbances introduced

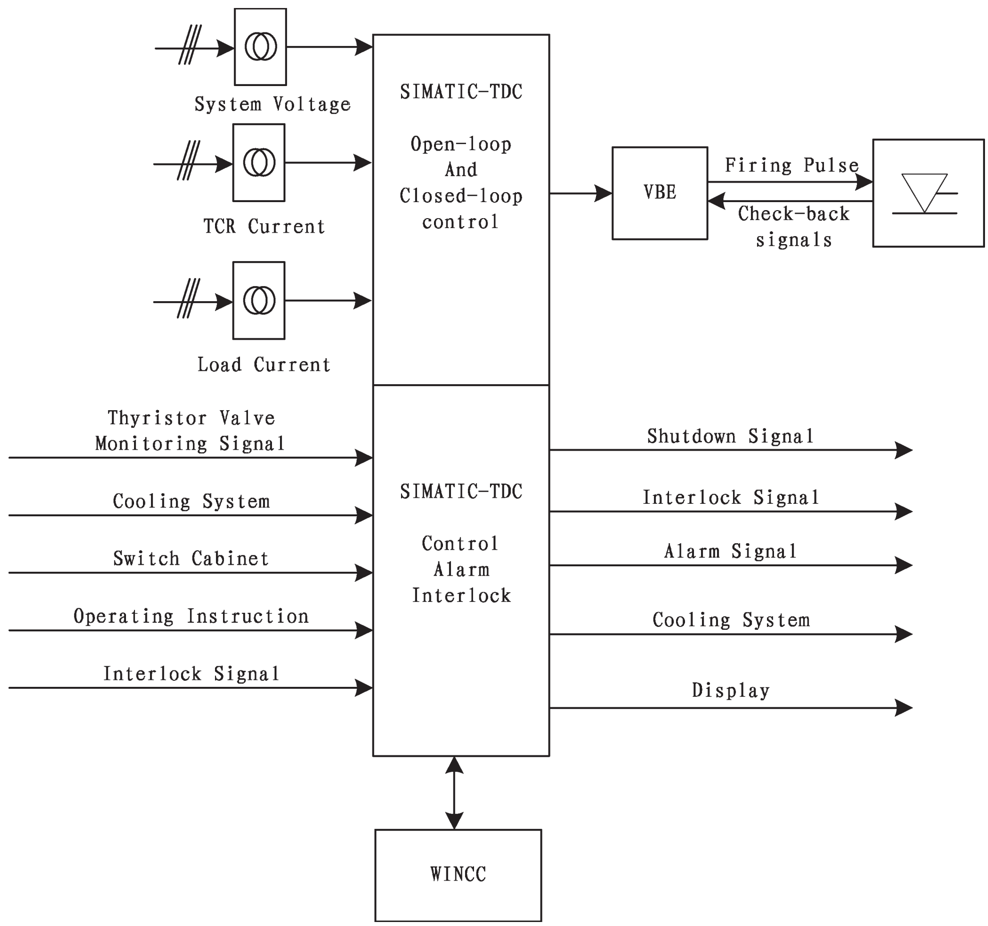


Fig. 4. SVC control system based on WIN-TDC.

by error signals and restrict fluctuation caused possibly by tuning the parameters or switching the control rules. This enhances the stability of the fuzzy control system.

When a large error exists, the main task of the controller is to diminish the error as quickly as possible. Thus, the error signal should be contributed more to the control actions, i.e., E should be a larger weight value. When the error is relatively small, the main purpose of the controller is to restrain the overshoot and drive the system into a steady state as soon as possible. Hence, the change rate of the error should be weighed more. In addition, as a larger error change exists, the error change should be contributed more to the control actions to enhance system damp function, i.e., the factors α_{c} and α_{e} are both the function of error (E) and error change (EC). The following formulas are introduced to define the α_{c} and α_{e}, respectively:

$$\alpha_{\mathrm{e}} = \frac{|E| + \alpha_{e0}}{|E| + |EC^2/E| + 1} \tag{11}$$

$$\alpha_{\mathrm{c}} = \frac{|EC^2/E| + \alpha_{c0}}{|E| + |EC^2/E| + 1} \tag{12}$$

where $\alpha_{c0} + \alpha_{e0} = 1$.

The fuzzy control rules in the proposed controller are the algebraic representation of fuzzy input variables instead of fuzzy sets. When triangular membership functions are used, the control output of the proposed fuzzy controller is the algebraic presentation of input variables.

It is easy to design this fuzzy controller because of the design experience for conventional PID controllers, the industrial process experiences and the PSCAD/EMTDC simulation results. For example, the reactive power consumption and its change rate of the rolling mill vary with different thickness rolling plates, and these characteristics are very different between the rolling mill, the ac electric arc furnace, the dc electric arc furnace and the coal mining excavator.

To get high performance and reliability of the SVC, the excellent controller platform and HMI are used in the development of the SVC control system. The SIMATIC-TDC controller provided by SIEMENS A&D is especially designed for complex closed-loop control and float arithmetic operation. This multiprocessor automation system offers almost unlimited computational performance. Up to 20 64-bit RISC CPU modules can be operated synchronously in a single subrack. The hardware and software of this SVC control system is developed based on the SIMATIC-TDC controller. The HMI system is developed with the globally used HMI system WinCC. The scheme of the SVC control system based on WIN-TDC (SIMATIC-TDC and WinCC) is shown in Fig. 4. In the figure, two CPUs are used. Of course, more CPUs can be used if needed.

In the control system, the main tasks of SIMATIC-TDC are as follows:

1) signal gathering, digital filtering;
2) implementing the SVC control strategy proposed in this paper;
3) calculating the firing angle of TCR;
4) communicating with microcomputer-based protection devices;
5) communicating with the controller of the cooling system;
6) monitoring the status of the main equipment and auxiliary equipment;
7) exchanging information with valve base electronics (VBE);
8) communicating with the HMI system;
9) maneuvering sequences and interlocking.

The purpose of the maneuvering sequences and interlocking is to provide safe and reliable switching within the SVC system, a smooth start and stop of the SVC and smooth transitions between different modes of control. The functions of maneuvering sequences and interlocking are:

1) interlocking for all maneuverable breakers/switches;
2) handling manual orders from operator control to breakers and switches;
3) synchronization check;
4) ready for energizing.
5) ready for operation;
6) energize/deenergize;
7) start/stop sequence.

The VBE, which is composed of the thyristor control unit and thyristor monitoring unit, is developed based on a digital signal processor and complex programmable logic device. The control signals from the SIMATIC-TDC and the check-back signals from the thyristor voltage monitoring boards are received in the VBE and processed in the thyristor control and monitoring units.

The SVC design process falls into two categories: concept development in nonreal time and actual software development which utilizes real time digital simulator (RTDS). The nonreal time simulation for most control and protection function is tested in PSCAD/EMTDC V4.2. The SVC control system used for the RTDS tests consisted of the WIN-TDC control system identical to the hardware implemented at the site. The actual controller connected to the RTDS had access to the same voltage transformer (VT) and current transformer (CT) signals as implemented on site and returned firing pulses to the RTDS. The ± 10 V analog output signals of the RTDS are amplified to DC110V input signals to the actual SIMATIC-TDC control. Firing pulses from the VBE are connected to a digital input time stamp (DITS) card on the RTDS. The DITS card enables the RTDS to model switching of the thyristors digitally with almost the same accuracy as an analog system.

IV. Project Application

The SVC control system proposed in this paper has been applied to many SVC projects such as those at Shougang Steel-Plate Company, Tianjin Light-rail Transport Company and

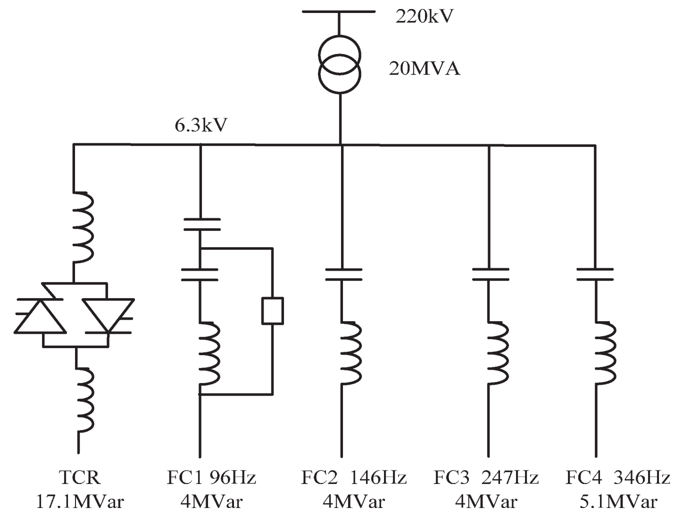


Fig. 5. Single-line diagram of Shougang Steel-Plate Company's SVC.

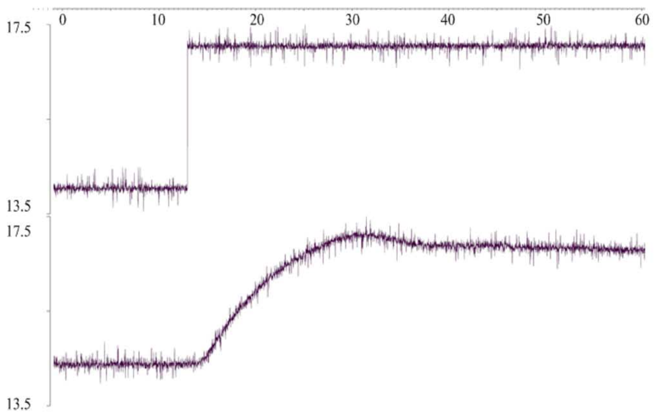
Bombardier Sifang Power Transportation, Ltd. As an example, the SVC project of Shougang Steel-Plate Company is briefed in this section. The purpose of the SVC is safeguarding power quality in the 220-kV grid supplying this plant.

The main load of the 220-kV substation of Shougang Steel-Plate Company is the rolling mills. The reactive power consumption of the mills has a bad influence on utilization of the main transformer, and their productive capacity is limited by the capability of the main transformer. To increase productive capacity, the reactive power must be dynamically compensated or a larger capability transformer should be used.

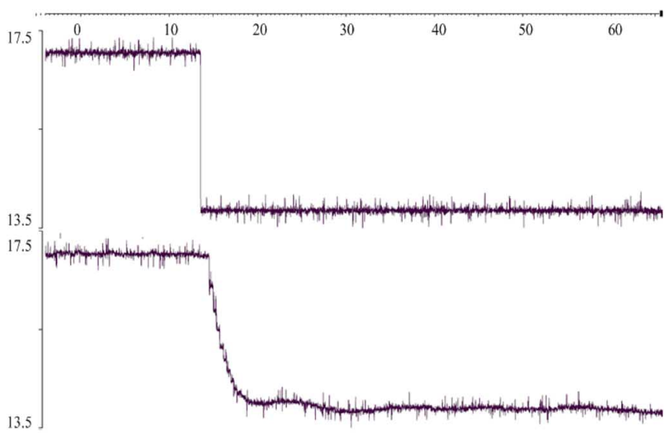
According to the 24 h (a whole production cycle) consecutive test, a 17.1 Mvar TCR + FC SVC is proposed to solve this problem. Fig. 5 shows the single diagram of this SVC. The Rolling Mill SVC comprises a TCR rated at 17.1 Mvar at nominal system voltage, a second C-type harmonic filter rated at 4 Mvar, a third harmonic filter rated at 4 Mvar, a fifth harmonic filter rated at 4 Mvar, and a seventh harmonic filter rated at 5.1 Mvar. The overall rating of the SVC is $0 \sim 17.1$ Mvar (capacitive), continuously variable.

The operation of this 17.1-Mvar SVC has improved the power quality, enhanced the voltage stability, and boosted the quality and output of the steel plate.

During field tests, the response of the SVC control system to step change of the reactive power is obtained by switching on an ac filter subbank. The step response test result is shown in Fig. 6. Data were recorded by a transient fault recorder. Curve 1 is the capacitive reactive power output by the ac filters, while Curve 2 is the reactive power generated by TCR. At first, the ac filter FC1, FC3, FC3 (tuned at 247 Hz) and FC4 are all switched on, and the total capacitive reactive power was 14.1 Mvar. TCR then outputs about 14.1 Mvar of inductive reactive power at the firing angle of 110°. When FC2 was switched on, the total capacitive reactive power changed to 17.1 Mvar, the TCR output became 17.1 Mvar at the firing angle of 159° within 10 ms, and the maximum overshoot is less than 10% of the ordered change. When FC3 was switched off, the total capacitive reactive power changed back to 14.1 Mvar, so the output of TCR changed back to about 14.1 Mvar inductive reactive power



(a)



(b)

Fig. 6. Dynamic characteristic tests of the proposed SVC control system. (a) Reactive power step-up response test by switching on a shunt capacitor. (b) Reactive power step-down response test by switching off a shunt capacitor.

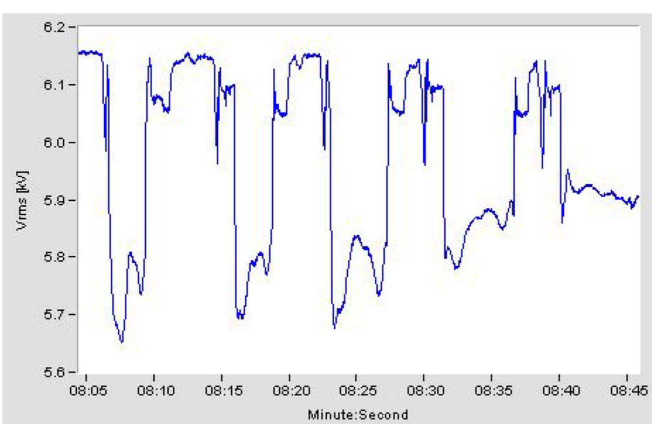


Fig. 7. Voltage of 6-kV busbar without SVC.

at the firing angle of 110° within 10 ms. The SVC control strategy proposed in this paper thus has good dynamic performance [21].

The curves of the 6 kV busbar voltage rms without and with the SVC that were recorded from the field tests are shown in Figs. 7 and 8. Without the SVC, the reactive power impact of the rolling mill led to frequent voltage drops, of which the amplitude is about 7%. After the SVC starts operation, the voltage drop was less than 0.5%.

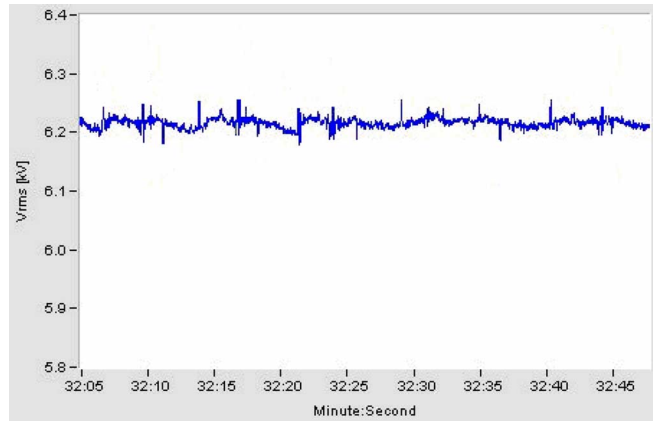


Fig. 8. Voltage of 6-kV busbar with SVC.

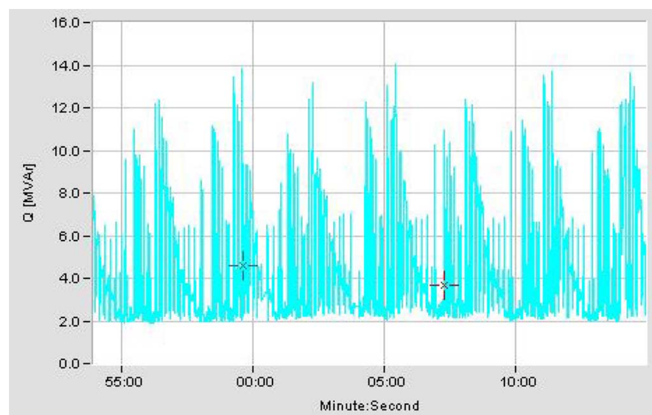


Fig. 9. Total reactive power of 6-kV busbar without SVC.

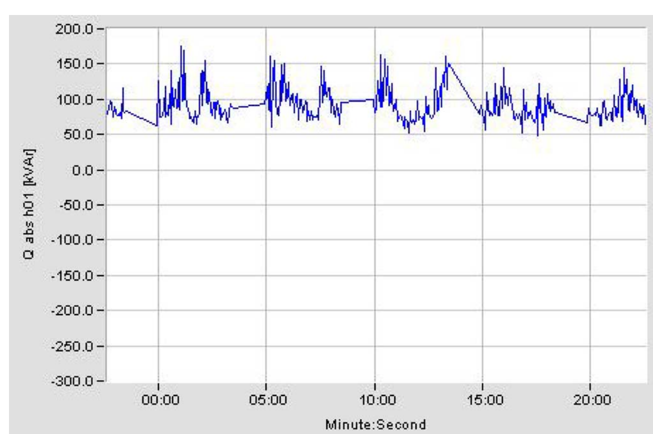


Fig. 10. Total reactive power of 6-kV busbar with SVC.

The reactive power of the 6-kV busbar without and with the SVC that were recorded from the field tests are shown in Figs. 9 and 10. Without the SVC, the reactive power consumption of the 6-kV busbar reached 14 Mvar. With the SVC, the reactive power was less than 200 kvar.

The power factors of the 6-kV busbar without and with the SVC that were recorded from the field tests are shown in Figs. 11 and 12. Without the SVC, the power factor of the 6-kV busbar reached almost 0.1. With the SVC, the power factor of the 6-kV busbar was maintained at 0.99.

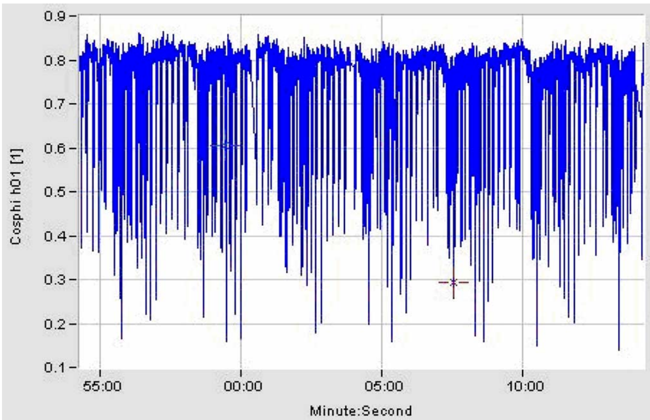


Fig. 11. Power factor of 6-kV busbar without SVC.

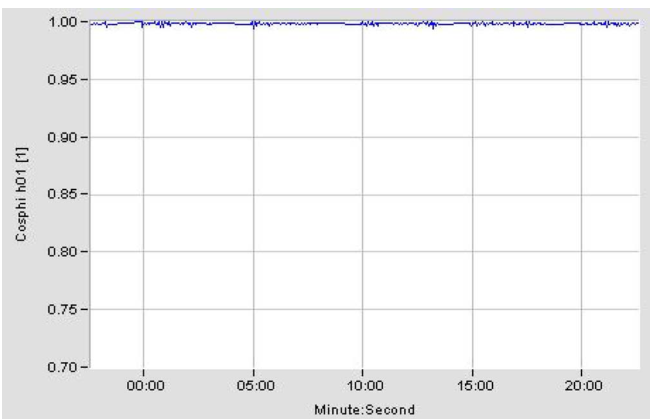


Fig. 12. Power factor of 6-kV busbar with SVC.

The active power of the 6-kV busbar without and with the SVC for the same rolling process, which were recorded from the field tests, are shown in Figs. 13 and 14. Without the SVC, the maximum active power consumed by the rolling mills during the biting course was about 12 MW. With the SVC, this value reached 16 MW. This means that rolling power and speed have been boosted and productive efficiency and capacity improved. The statistical analysis showed that the output of the same steel plate has increased 20%.

With the SVC in operation, the following required performance is met as shown in the Table I.

As discussed before, to increase productive capacity two methods were considered for Shougang Steel-Plate Company: one was to compensate the reactive power dynamically with a SVC, and the other was to replace the main transformer with a new one with larger capability. Using the latter method, the cost of the new transformer was almost identical to the SVC, the old transformer had to be discarded, the rolling mills had to be stopped to replace the transformer, and the power quality problem would still exist. Another advantage of the former is that the quality of rolling plates have been improved due to almost no voltage drop during the rolling mill operation, and this result has been proven by the tests of Quality Control and Inspection Center of Shougang Steel-Plate Company. Due to a higher power factor and almost no reactive power consumption, the electric cost has decreased 10%.

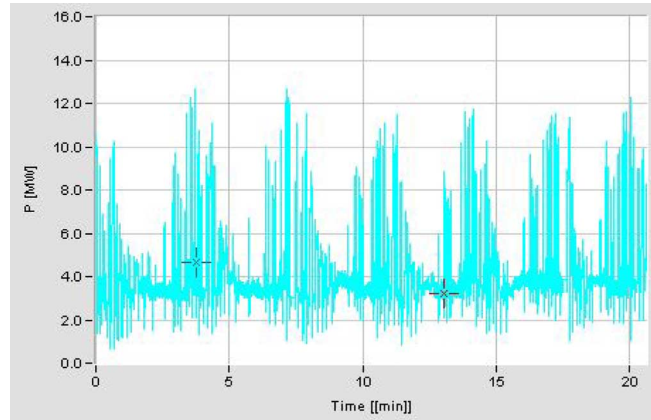


Fig. 13. Active power of 6-kV busbar without SVC.

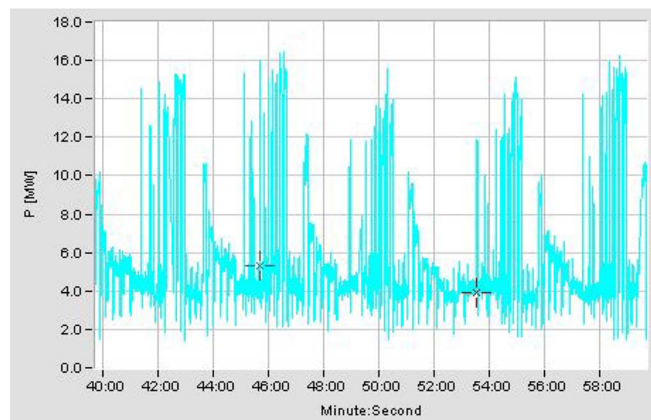


Fig. 14. Active power of 6-kV busbar with SVC.

TABLE I
INDEXES OF POWER QUALITY WITH AND WITHOUT SVC

Item	Without SVC	With SVC
Flicker reduction factor at the 220 kV PCC	Pst ≈ 3	Pst < 0.7
Power factor at the 220 kV feeder when rolling mill running	PF ≈ 0.4	PF > 0.99
Voltage unbalance at the 220 kV PCC	$\varepsilon_u \approx 2\%$	$\varepsilon_u < 0.5\%$
Voltage fluctuations at the 6.3 kV rolling mill bus	d ≈ 7%	d < 1%
Harmonic voltage distortion at 6.3 kV rolling mill bus	THD < 5%	THD < 1%

For the SVC at Tianjin Light-rail Transport Company, the economic index was very clear. Due to the power quality problem the fine imposed by the electric utility was about 900 000 RMB (about $115000) per month, and after installing the SVC, the company is awarded 30000 RMB (about $3800) per moth.

V. CONCLUSION

In this paper, a phase-to-phase "open + close" control strategy for industrial SVCs was proposed. The forward loop is to guarantee short response time, while the feedback loop is to ensure good dynamics and steady characteristics of the SVC. Regulated ranges are different for the open-loop and close-loop. The fast compensation algorithm for asymmetric industrial loads based on instantaneous reactive power theory is used in the forward loop, while a fuzzy PID is applied to the close loop. The hardware and software of this SVC control system is developed based on SIMATIC-TDC and WinCC, in which the former is the most modern but well-proven industrial controller, and the latter is the globally used HMI system.

The SVC control system proposed in this paper has been applied to many SVC projects in China such as that at Shougang Steel-Plate Company, Tianjin Light-rail Transport Company and Bombardier Power Transportation Company. The field test results show the SVC control system presented in this paper has a perfect dynamic and static performance.

The scheme of SVC control system based on WIN-TDC (SIMATIC-TDC and WinCC) proposed in this paper can be applied to other FACTS, such as STATCOM, thyristor controlled series compensator and high voltage direct current transmission.

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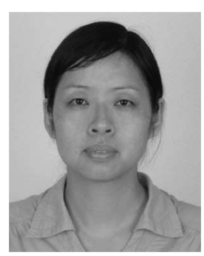

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