Reactive Power Compensation Characteristics of a New SVC for Industry Custom Power System

Fang Liu, Ryuichi Yokoyama, Yicheng Zhou, Yong Li, Min Wu

Abstract--**This paper proposes a new industry custom power system with a new static var compensator (SVC) main circuit topology, and then introduces the wiring scheme of the new rectifier transformer, the harmonic suppression mechanism of the inductive filtering different from the traditional passive filtering (PF) and the active filtering (AF), and the dynamic reactive compensation at the third side of the new rectifier transformer. Based on this, the operation mechanism of the inductive filtering and the reactive compensation that the new SVC has are theoretically analyzed in detail. The simulation results verify the correctness of the theoretical analysis mentioned above, and expressed the good effects of the unique inductive filtering and the reactive compensation that the new SVC has.**

***Keywords*: SVC, reactive power compensation, rectifier transformer, custom power, harmonic.**

I. Introduction

As for the industry custom power systems such as the applications in the chemical engineering, metallurgical plant, paper mill, etc, there are always the rectifier systems, which are used to provide the dc power source for the manufacturing production[1~3]. However, because of the wide use of power electronic elements in the rectifier systems and various nonlinear electrolysis loads, a large number of harmonic currents will be generated at the ac side, and meanwhile, the operation of the rectifier needs great reactive power from the ac grid [4~6], which inevitably increase the additional operational loss of the main electrical equipments such as the rectifier transformer, reduce the power factor of the ac system, and leads to vibration and high frequency noise.

At present, the usual solutions to the problems mentioned above are place the various filtering and var compensation equipments, such as the passive power filter (PPF) [7], the active power filter (APF) [8], the parallel capacitor, the static var compensators (SVC) [9] or the static compensators (STATCOM) [10], at the grid side of the industry custom power systems. Although these solutions can improve the power quality of the ac grid side caused by harmonic currents and reactive power, it could be found that these negative effects on the rectifier transformer cannot be solved radically. All the harmonic currents and reactive power component has to flow into the grid side via the rectifier transformer, so they will free flow in the secondary and the primary windings, which is advantage to the operation of the rectifier transformer, and increase the additional loss, vibration and noise. So, it can be seen that the convention methods cannot solve the contradiction between the ac grid and the main supplied equipments [11~13].

Different from the conventional industry rectifier system and the traditional filtering and var compensating methods, this paper will presents a new industry custom power system, which adopts the new rectifier transformer and the new static var compensator (SVC) with the new inductive filters. It can realize the goals of carrying out the dynamic reactive compensation and the harmonic suppression at the secondary side of the new rectifier transformer, which is advantage to the operation of the rectifier transformer, and can reduce the operational loss but increase the system power factor and the rectifier efficient at the same time. This paper will mainly analyze and calculate the special inductive filtering and the reactive power compensation characteristic that the new industry rectifier system has.

II. Main Circuit Topology of the New Rectifier System with New SVC

Fig.1 shows the topology of the main circuit of the proposed new rectifier system with the new SVC equipment for the custom power system, from which, it can be seen that the new rectifier transformer adopts three-winding structure, and its three winding is connected with the new SVC equipment. Different from the traditional three-winding transformer, during the impedance design for the new rectifier, it should ensure the zero-reactance design for the third winding to obtain the good inductive filtering effect.

As for the new SVC, it is made up of the inductive filters, the thyristor controlled reactor (TCR) and the thyristor switched capacitor (TSC). It is worth to say that in order to ensure the good inductive filtering effect, the impedance of the inductive filters under the special frequencies should be approximate equal to 0, which means that the inductive filters should satisfy the full-tuned design. However, as for the

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conventional PPF, in order to avoid the series resonance or parallel resonance under some harmonic frequency, the PPF should satisfy the bias-tuned design, which is different from the inductive filtering method. Considering that the orders of the characteristic harmonic currents generated by the 6-pulse SCR rectifier bridge are $6n\pm1$ (n=1,2,3,…), and in which the content of 5th, 7th, 11th, 13th harmonic currents is high at the ac side of the SCR, so the inductive filters are design to carry out full tuned under the above harmonic frequency orders. Meanwhile, the inductive filters can provide a part of reactive power for the SCR. As for TCR+TSC shown in Fig.1, they are used to realize the power factor (PF) control goal to ensure the high efficiency operation of the new industry rectifier system. It can carry out dynamically and continuous var compensation within the specified capacitive and the inductive reactive power by controlling the firing angle of the GTO in the TCR and TSC.

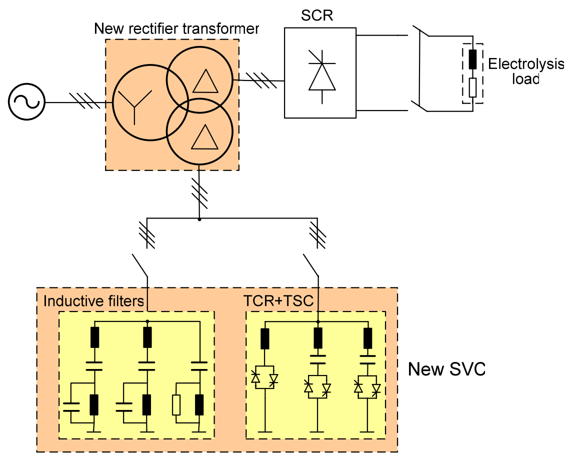


Fig.1. Main circuit topology of the new rectifier system with the new SVC

III. Operation Mechanisms of Inductive Filtering and VAR Compensating

A. Inductive Filtering

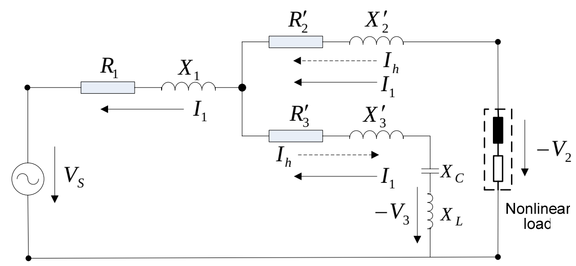


Fig.2. Single-phase equivalent circuit model of the new rectifier transformer

The inductive filtering mechanism can be explained by the single-phase equivalent circuit model of the new rectifier transformer shown in Fig.2. As for the harmonic current I_h generated by the nonlinear load such as the 5th harmonic current, it will flow into the secondary winding of the new rectifier system. If the harmonic voltage at the primary side is ignored, that is U_{Sh}=0, then, the harmonic current in the primary winding can be expressed as following:

$$I_{1h}=\frac{Z_{3h}'+Z_{fh}}{Z_{1h}+Z_{3h}'+Z_{fh}}I_h=\frac{1}{\dfrac{Z_{1h}}{Z_{3h}'+Z_{fh}}+1}I_h \tag{1}$$

In which, I_h expresses the harmonic current generated by the nonlinear load; Z_{1h} and Z'_{3h} express the harmonic equivalent impedance of the primary and the third windings of the new rectifier transformer for the specific harmonic frequency respectively; Z_{fh} expresses the harmonic impedance of the inductive filter.

As for the harmonic equivalent impedance of the windings, it can be further expressed as follows:

$$\begin{cases} Z_{1h}=R_1+jhX_1 \\ Z_{2h}'=R_2'+jhX_2' \\ Z_{3h}'=R_3'+jhX_3' \end{cases} \tag{2}$$

In which, R_1, R'_2, and R'_3 express the effective resistance of the primary, the secondary, and the third winding; X_1, X'_2, and X'_3 express the equivalent reactance of the above corresponding windings; h expresses the specific harmonic order.

The above parameters of the new rectifier transformer can be obtained by three short-circuit tests. And the effective resistance and the equivalent reactance can be respectively obtained as follows:

$$\begin{cases} R_1=\dfrac{R_{1-2}+R_{1-3}-R_{2-3}}{2} \\ R_2=\dfrac{R_{1-2}+R_{2-3}-R_{1-3}}{2} \\ R_3=\dfrac{R_{1-3}+R_{2-3}-R_{1-2}}{2} \end{cases} \tag{3}$$

$$\begin{cases} X_1=\dfrac{X_{1-2}+X_{1-3}-X_{2-3}}{2} \\ X_2=\dfrac{X_{1-2}+X_{2-3}-X_{1-3}}{2} \\ X_3=\dfrac{X_{1-3}+X_{2-3}-X_{1-2}}{2} \end{cases} \tag{4}$$

In which, $R_{1\text{-}2}$, $R_{1\text{-}3}$, and $R_{2\text{-}3}$ express the short-circuit resistance; $X_{1\text{-}2}$, $X_{1\text{-}3}$, and $X_{2\text{-}3}$ express the short-circuit reactance. All the values can be determined by the short-circuit test results.

According to equation (1), it can be found that if Z_{1h}>>(Z_{3h}+Z_{fh}), then $I_{1h}\approx0$, which means that there will be no the specific harmonic current in the primary winding, and further means that the specific harmonic current is suppressed to only flow in the secondary and the third winding. In order to ensure the above condition, we can further obtain that (Z_{3h}+$Z_{fh}\approx0$, which means that under the specific harmonic frequency, the parameters related to Z_{3h} shown in equation

(2)~(3) should be approximate equal to 0, and the harmonic impedance of the inductive filter shown in Fig.2 should satisfy the following equation (5):

$$Z_{fh} = -j\frac{1}{h\omega C} + jh\omega L = 0 \tag{5}$$

In which, ω expresses the fundamental angular frequency, and $\omega = 2\pi f$; L and C expresses the value of filtering capacitor and filtering reactance of the inductive filter.

From the above circuit analysis, it can be found that the inductive filtering needs the zero-impedance circuit composed with the zero-impedance of the third windings of the new rectifier transformer and the zero-harmonic-impedance of the inductive filters under the specific harmonic frequency. In this way, it can realize the harmonic shielding with the primary winding and the power grid.

Meanwhile, from Fig.2, it can be found that as for the fundamental current I1, because that the inductive filter express the capacitive feature under the fundamental frequency, so it can compensate the reactive power at the same time of the inductive filtering.

B. Reactive Power Compensation

According to the topology of the new rectifier transformer shown in Fig.1, the corresponding voltage vector diagram can be obtained shown in Fig. 3, in which, $V_{Ai\text{-}Bi}$, $V_{Bi\text{-}Ci}$, and $V_{Ci\text{-}Ai}$ (i=2,3) express the three-phase line voltage between *A*- and *B*-phase, *B*- and *C*-phase, and *C*- and B-phase, respectively, which also express the secondary and the third windings' voltage. $V_{Ai\text{-}0}$, $V_{Bi\text{-}o}$, and $V_{Ci\text{-}0}$ express the phase voltage at the primary side, which also express the primary windings' voltage.

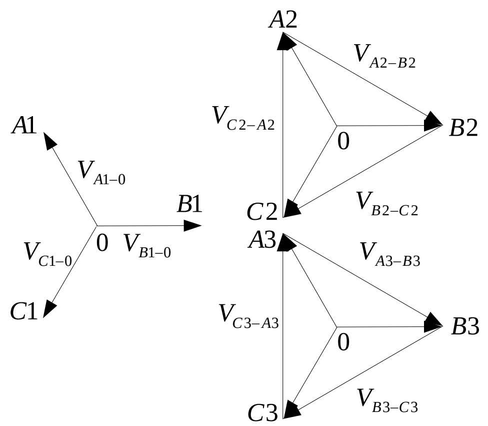


Fig.3. Voltage vector diagram of the new rectifier transformer

When the third winding is connected with the new SVC equipment, in general, the SVC will provide the capacitive reactive power for the operation of the SCR. In that case, the current $I_{A3\text{-}0}$ in the third winding will lead 90^o to the phase voltage $V_{A3\text{-}0}$ of the third winding, which can be shown in Fig.4. Assume that the load current I_{AL} lag φ to the phase voltage $V_{A2\text{-}0}$, that is, the power factor is equal to $\cos\varphi$, then according to the transformer's magnetic balance and the vector relationship shown in Fig.4, it is easy to obtain the primary phase current $I_{A1\text{-}0}$. It can be seen that by the var compensation at the third windings, the power factor at the grid side is closed to 1.

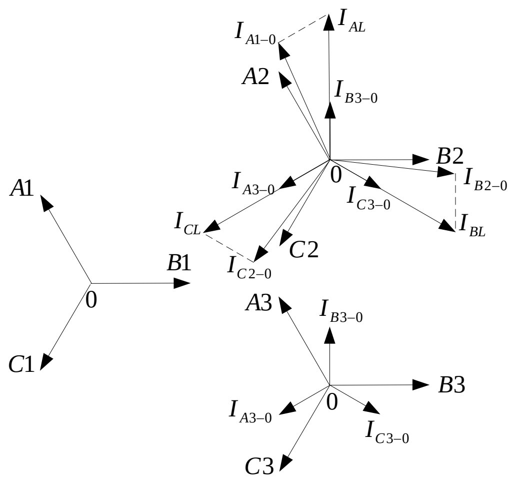


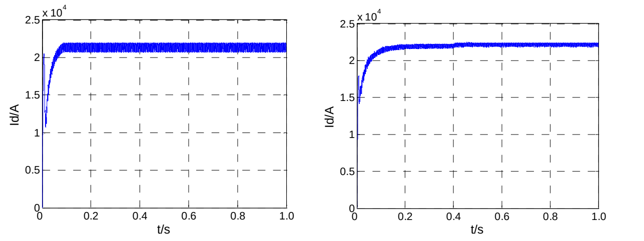
Fig.4. Reactive power compensation characteristic of the new SVC

IV. System Simulation Study

According to the main circuit topology of the new rectifier system shown in Fig.1 and the inductive filtering and var compensating characteristics mentioned above, the simulation system can be established to verify the correctness of the above theoretical analysis. As for the simulation system, the rated dc current I_{dc} is 22kA, dc voltage V_{dc} is 415V; the voltage of the primary, the secondary, and the third windings of the new rectifier transformer is 25200V, 350V, and 10000V, respectively.

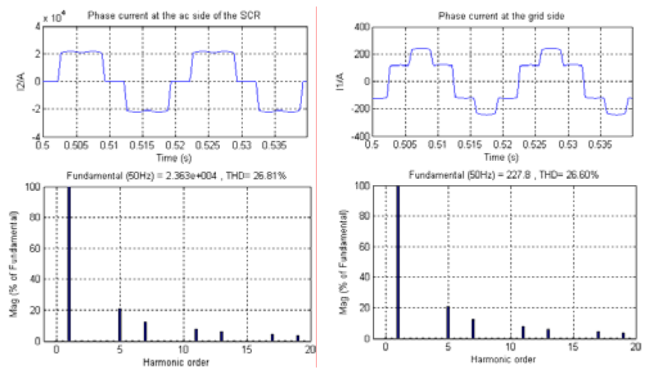
A. Effect of the Inductive Filtering Method

Fig.5 shows the simulation results of the dc current of the new rectifier systems when adopts the new SVC or not, and Fig.6 and 7 respectively express the phase current and its FFT at the secondary and the primary side of the new rectifier transformer when the system adopts the new SVC or not. From the simulation results, it can be seen that weather adopt the new SVC or not, the harmonic characteristic is similar shown in Fig.6(a) and Fig.7(a), which is determined by the operational characteristic of the SCR. As for the 6-pulse SCR bridge, the characteristic harmonic order at the ac side is 6n$\pm$1 (n=1,2,3,…). While compared Fig.6(b) and Fig.7(b), it can be seen that when adopt the new SVC, because that it contains the inductive filters for 5th, 7th, 11th, 13th harmonic currents, so it can effectively suppress these harmonic in the secondary and the third winding, and the harmonic content of the current in the primary winding is very low. The THD is from 26.60% to only 2.03%, which indicates the good filtering effect that the inductive filtering has.



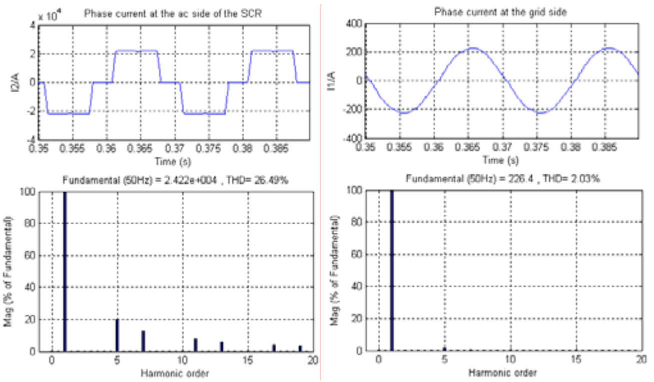
(a) (b)

Fig. 5. DC currents of the new rectifier system with or without the new SVC. (a) without the new SVC. (b) with the new SVC.



(a) (b)

Fig.6. Phase current and its FFT at the secondary and the primary side of the new rectifier transformer without the new SVC in the system. (a) at the secondary side. (b) at the primary side.

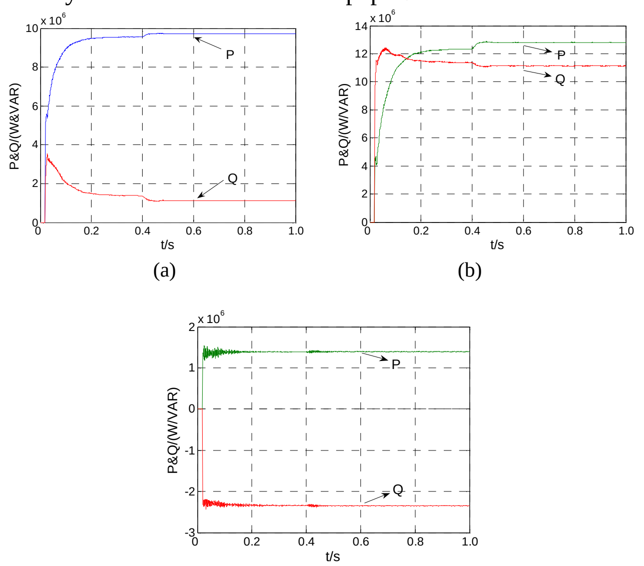


(a) (b)

Fig.7. Phase current and its FFT at the secondary and the primary side of the new rectifier transformer with the new SVC in the system. (a) at the secondary side. (b) at the primary side.

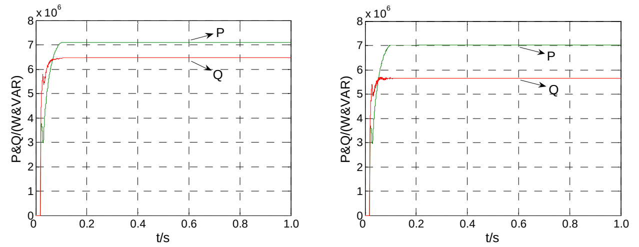
B. *Characteristic of the Reactive Power Compensation*

Fig.8 and 9 respectively express the active and the reactive power (P&Q) simulation results when the new rectifier system adopts the new SVC or not. Through comparing, it can be found that by the var compensation of the new SVC at the third side of the new rectifier transformer, the reactive power at the grid side can be reduced from about 6.5MVAR to about 1.6MVAR shown in Fig. 8(a) and Fig.9(a). The power factor at the grid side is increased from about 0.75 to about 0.98, which can be seen in Fig. 10(a) and Fig. 11(a). As for the reactive power at the secondary side of the new rectifier transformer, because that the SCR needs large number of reactive power during the communication course, so there are lots of lag reactive power shown in Fig.8(b) and Fig.9(b), and both the power factors are 0.77~0.78 shown in Fig.10(b) and Fig.11(b). However, from Fig.8(c), it can be seen that the new SVC can provide the lead reactive power to a certain to satisfy the demand of the SCR, so the SCR needn't the reactive power from the power grid. Also, it is worth to say that, similar with the conventional SVC, the new SVC has to consume a certain active power. But because that the new SVC is connected at the medium-voltage side different from that of the conventional SVC connected at the high-voltage grid side, so the operation loss could be reduced, which will be analyzed in detail in the future paper.



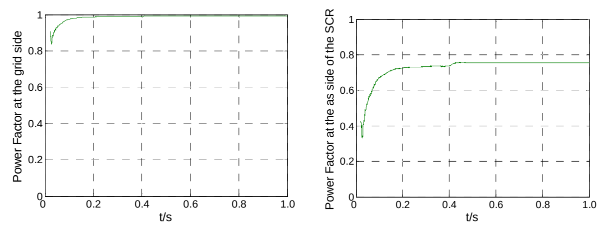
(c)

Fig.8. Active and reactive power (P&Q) at the primary, the secondary, and the third side of the new rectifier transformer with the application of the new SVC in system. (a) at the primary side. (b) at the secondary side. (c) at the third side.



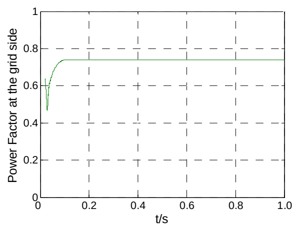
(a) (b)

Fig.9. Active and reactive power (P&Q) at the primary and the secondary side of the new rectifier transformer without the application of the new SVC in system. (a) at the primary side. (b) at the secondary side.

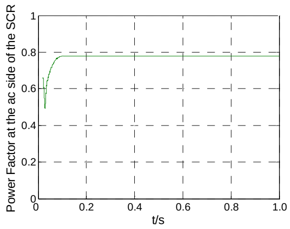


(a) (b)

Fig.10 Power factor at the primary and the secondary side of the rectifier transformer with the application of the new SVC in system. (a) at the primary side. (b) at the secondary side.



(a)



(b)

Fig.11 Power factor at the primary and the secondary side of the rectifier transformer without the application of the new SVC in system. (a) at the primary side. (b) at the secondary side.

V. CONCLUSIONS

This paper presents a new rectifier system with a new SVC for the custom power systems. The new SVC contains the inductive filters, which can not only suppress the main harmonic currents generated by the TCR, but also suppress the main harmonic currents generated by the SCR, and shield them with the primary side and the power network, which is advantage to the operation of the rectifier transformer. Moreover, it can provide a certain reactive power near the SCR side. The detail simulation results verified the theoretical analysis, and express the good effects of the inductive filtering and the reactive power compensation that the new SVC has.

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