Implementation of a Shunt-Series Compensator

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Abstract— **This paper presents the system analysis and circuit implementation of single-phase shunt-series compensator to improve voltage and current quality at the load side. The series compensator is adopted to compensate the voltage disturbance including voltage sag, swell, flicker and harmonics. The shunt compensator is used to supply the necessary active current to main the constant dc-link voltage of the inverter and to improve the power quality of utility source including the reactive current and harmonic current. The full-bridge inverters are used in the series and shunt compensator with the common dc-link. The full-bridge inverter has less voltage stress of power semiconductor compared with the voltage stress of switching devices in the half-bridge inverter. There is an active power flow between the series and shunt compensators to main the dc-link voltage constant when voltage disturbance is detected at the point of common coupling. The system analysis and operational principle of the adopted system is presented. Some experimental results of a scale-down prototype circuit are presented to verify the effectiveness and validity of the proposed control scheme.**

Index Terms– **series compensator, shunt compensator, harmonic, voltage sag.**

I. INTRODUCTION

Power quality problems have been become serious problem due to a large number of nonlinear load used in the modern industry products such as switching mode power supplies, electronic fluorescent lamps, industrial motor drives and uninterruptible power supplies. High quality source current and stable source voltage are generally welcome in the utility and load sides. To overcome the above problems high quality ac compensator operated with low harmonic current, high power factor, low total harmonic distortion and high reliability have been developed. The shunt compensator or shunt active filters were used to improve the power quality of the ac source. The shunt compensator is operated as a controllable current source to supply the currents that are equal to the harmonic and reactive components of nonlinear load. The utility system only supplies active current component to the load such that the system power factor is close to unity. A clean and stable ac source is required in the voltage-sensitive equipment such as computers, telecommunication the system power factor is close to unity. A clean and stable ac source is required in the voltage-sensitive equipments such as computers, telecommunication systems and biomedical instrumentations. Voltage regulators and uninterruptible power supplies (UPS) have capability to provide the stable sinusoidal voltage that is independent of the mains voltage to the critical load. However the cost of the UPS system is very expensive. The series-connected compensators or series active filters were proposed to protect the sensitive load against the voltage disturbances due to short-term abnormal voltage conditions. The technique of series compensator is an effective and cost competitive approach to improve voltage quality at the load side.

A shunt-series compensator is presented in this paper to compensate current quality at the utility side and voltage quality at the load side for the nonlinear and voltage sensitive load. Two full-bridge inverters with a common dc bus are used in the adopted shunt-series compensator. The shunt compensator can supply the harmonic and reactive components of nonlinear load current and draw or inject the active current from or to the system under the voltage sag or swell condition. Therefore the dc-link voltage can be maintained at the constant value. The series compensator can maintain the load voltage at the desired root mean square under the abnormal utility conditions. When voltage disturbance is detected at the load side, the series compensator is operated as a controllable voltage source to protect the voltage sensitive load against abnormal voltage disturbance. The single-phase shunt-series compensator based on full-bridge inverter topology for low power application is studied to improve the current and voltage qualities. The system operation and control approach are presented. The experimental results are presented to verify the validity and effectiveness of the control algorithm.

II. CONFIGURATION OF SHUNT-SERIES COMPENSATION

Fig. 1(a) gives the conventional voltage compensator. The ac/dc converter is used to achieve power factor correction and maintain the dc link voltage at the constant value. The dc/ac inverter is adopted to generate the stable load voltage to the voltage sensitive load. Therefore the load voltage is insensitive to the voltage disturbance. However the power rating of conventional ac/dc/ac converter is equal to the rated load power. The cost of this compensator is very high. Fig. 1(b) gives the system configuration of adopted shunt-series compensator for nonlinear and voltage sensitive load. Two voltage source inverters are used in the compensator. The series compensator is connected in series between the utility and load through an isolation transformer. The series compensator is operated in the voltage-controlled mode to inject or extract the compensating voltage to against the voltage disturbance such as voltage sag or swell at the load side. Therefore the load voltage is maintained at the stable root mean square value. The shunt compensator is connected in parallel with the load. The shunt compensator is operated in the current-controlled mode to supply the necessary active current for dc bus voltage regulation as well as to compensate the harmonic and reactive currents generated from the nonlinear load such that the power factor at the utility side is close to unity. The power rating of the adopted voltage compensator is only one part of rated load power. Therefore the cost of the adopted compensator is lower than the cost of conventional ac/dc/ac compensator. Fig. 2 gives the equivalent circuit of shunt-series compensator for current and voltage quality compensation.

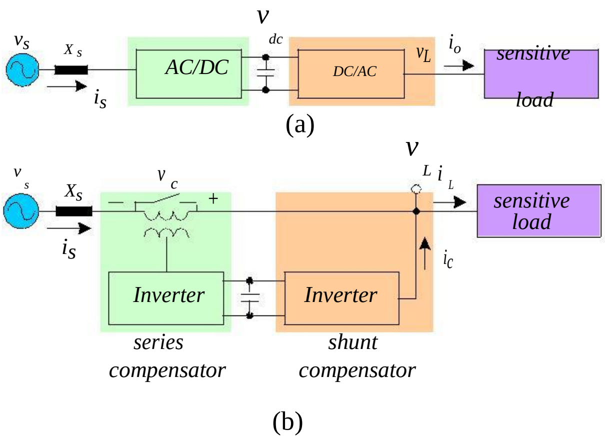


Fig. 1 (a) Conventional AC/DC/AC voltage compensator (b) adopted shunt-series voltage compensator.

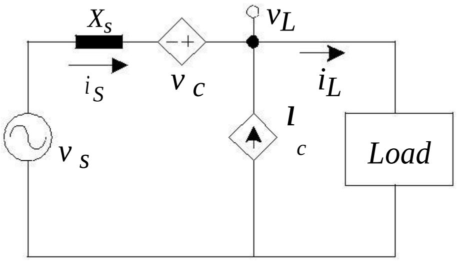


Fig. 2 Equivalent circuit of the shunt-series compensator.

The circuit topologies of shunt-series configuration can be two half-bridge inverters or two full-bridge inverters connected with a common dc link. Fig. 3 gives the shunt-series compensator based on two half-bridge inverters with the reduced number of switching devices and control functions for low power system. Two switches and two split capacitors are used in each inverter to generate the bipolar pulse-width modulation (PWM) waveforms on the ac side. Fig. 4 illustrates the circuit configuration of single-phase shunt-series compensator based on two full-bridge inverters. The shunt-connected inverter consists of four switching devices and one dc bus capacitor to achieve unipolar PWM operation. The fullbridge based topology has better voltage utilization and less harmonic content of compensating voltage and current compared with that of half-bridge based topology.

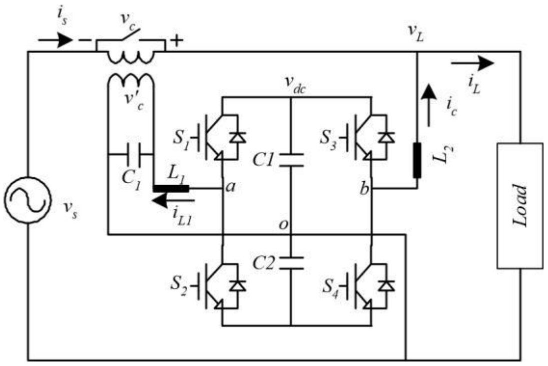


Fig. 3 Circuit configuration of single-phase shunt-series compensator based on two half-bridge inverters.

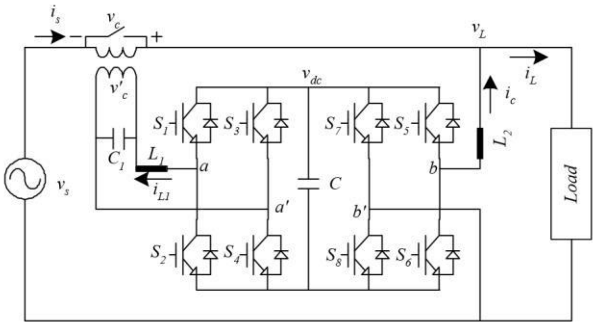


Fig. 4 Circuit configuration of single-phase shunt-series compensator based on two full-bridge inverters.

III. SYSTEM ANALYSIS AND OPERATION PRINCIPLE

The adopted shunt-series compensator is controlled to perform the following goals: 1) sinusoidal line current, 2) unity power factor, 3) constant dc link voltage, and 4) stable load voltage. Before analysis of the proposed converter, the power switches are assumed ideal and two switches in each inverter leg are complementary each other to avoid the power switches conducting at the same time. The relationships between the ac side voltages and the dc bus voltage of the proposed compensator are given as

where *vaa'* and *vbb'* are the ac side voltages of the series and shunt compensators, respectively, *vdc* is the dc bus voltage. Based on the on/off state of each switching devices, three voltage levels *vdc*, 0 and -*vdc* are generated on the ac terminal voltages *vaa'* and *vbb'*. The compensating voltage of series compensator is based on the desired load voltage command and the measured load voltage. In the series compensator, the voltage level *vdc* and 0 are generated on *vaa'* during the positive compensating voltage. On the other hand, another two voltage levels -*vdc* and 0 are generated on voltage *vaa'* during the negative compensating voltage. For the shunt compensator, the compensating current is based on the reference line current command and the measured line current. During the positive load voltage, two voltage levels *vdc* and 0 are generated on the *vbb'* to control the compensating current to follow the current command. On the other hand another two voltage levels -*vdc* and 0 are generated on ac terminal voltage *vbb'* to track the reference compensating current.

turn ratio of isolation transformer. Fig. 5 gives the equivalent circuit of the shunt-series compensator based on the above analysis. The above equations of the adopted system can be used to to achieve high input power factor, regulate DC bus voltage and provide the stable sinusoidal output voltage using the computer simulation software.

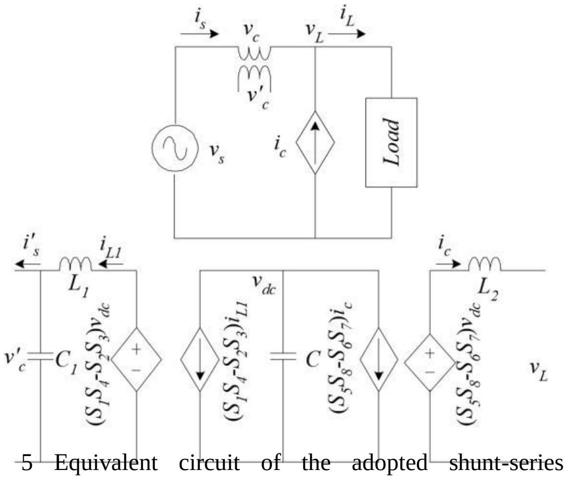


Fig. 5 Equivalent circuit of the adopted shunt-series compensator.

IV. CONTROL STRATEGY

Based on the proposed control scheme the adopted compensator can achieve power factor correction, draw a sinusoidal line current, regulate dc bus voltage, and provide a stable load voltage.

A. Shunt Compensator

Three valid operation modes are used to generate three voltage levels on the ac terminal of the shunt compensator. Based on the load voltage and the line current error, the appropriate switching state of *S5~S8* can be selected to generate proper voltage level on the ac terminal and to track the line current command. The actual line current will track the line current command with the current slope of (*vL-vbb'*)/*L2* by controlling the voltage *vbb'*. During the positive and negative load voltage, one high voltage level and one low voltage level are used to control the line current. During the positive load voltage, two voltage levels *0* (*S6=S8=1*) and *vdc* (*S5=S8=1*) are generated on the voltage *vbb'*. Power switch *S8* is always turned on in the positive load voltage. High voltage level *vdc* generated on the ac side voltage *vbb'* will decrease line current. Low voltage *vbb'*=0 will increase line current in the positive half cycle of mains voltage. During the negative half cycle of load voltage, another two voltage levels 0 (*S5=S7=1*) and -*vdc* (*S6=S7=1*) are generated on the ac side and to control line current. For each half cycle of load voltage, the low voltage level is selected to increase the line current and high voltage level is used to decrease the line current. Fig. 6 shows a control block diagram of the shunt compensator. To improve the dynamic response and eliminate the steady-state error of dc bus voltage, a proportional-integral voltage controller is used in the inner control loop to determine the active source current command I^*s. When mains voltage or load voltage variation is detected, the real power between the load and utility is not be sustained. The real source power is changed by adjusting the line current command to match the real power variation of the load. A phaselocked loop (PLL) circuit is adopted to produce a reference sinusoidal wave in phase with mains voltage. The current error between the source current command and measured current is sent to the current controller. The hysteresis current comparator is used in the current control loop to track the source current command i^*s. Three voltage levels (*vdc*/2, 0, and -*vdc*/2) can be generated on the ac side of the rectifier.

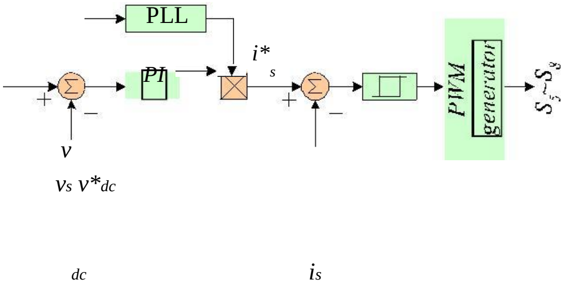


Fig. 6 Control block diagram of the shunt compensator for power factor correction.

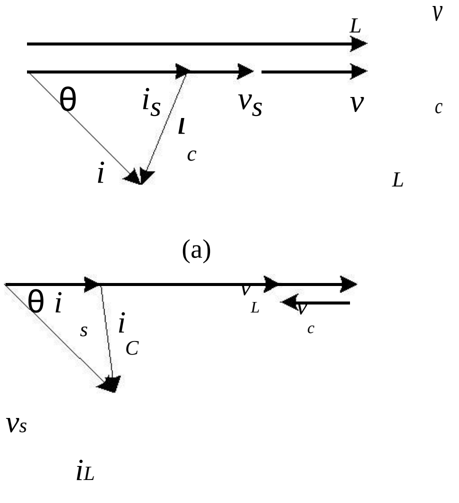
B. Series Compensator

In the adopted series compensator, four power switches *S5~S8* are used. Inductor *L1* and capacitor *C1* are used to eliminate the voltage harmonics for generate the compensating voltage waveform to protect the sensitive load. The series compensator can achieve both directions of voltage regulation such as voltage sag and swell. Under the voltage sag condition, the series compensator generates the compensating voltage at the isolation transformer such that the load voltage is a sinusoidal voltage in phase with source voltage. Fig. 7(a) shows the phasor diagram of the series compensator under the source voltage sag condition. Normally the phase angle of load current is less than 90 degree. Therefore the series compensator should supply active power to the load under the voltage sag condition. This active power is supplied from the shunt compensator by regulating the dc-link voltage. An active current from the load side is flowing through the shunt compensator to dc bus. Under the voltage swell condition, the generated voltage at the output side of the series compensator should be out of phase of the source voltage. Fig. 7(b) gives the phasor diagram of the adopted series compensator operating at the voltage swell condition. To keep the dc bus voltage at the desired value, an active power absorbed by the series compensator should be delivered into the load side through the shunt compensator. Therefore an active current is supplied by the shunt compensator and flows to the load side.

Fig. 8 shows the control block diagram of the series compensator under the voltage disturbance condition. First the root mean square value of load voltage is measured and compared with the desired voltage command. The dc voltage controller based on a proportional plus integral control is used to obtain the amplitude of the compensating voltage command *V*c*. The phase locked loop circuit is used to generate the unit sinusoidal wave in phase with source voltage. The compensating voltage command and the measured compensating voltage are compared to obtain the voltage error. A proportionalintegral (PI) voltage controller is used to obtain the compensating current to improve the output voltage regulation. Therefore, the calculated reference inductor current *i*L1* is equal to

$$i_L^* = i'_s + i_{comp} = i'_s + k_p \Delta v'_c + k_i \int \Delta v'_c \, dt \qquad (5)$$

where *i's* is the current at the output side of the series compensator, *kp* and *ki* are the proportional and integral gain of the voltage controller. The inner inductor current controller is adopted to improve the dynamic response of the load change. The carrier-based PWM schemes are used to generate the switching signals of power switches *S1~S4*. Based on the switching signals of power switches, a unipolar PWM voltage waveform is generated on the ac side of the series compensator.



(a)

(b)

Fig. 7 Phasor diagram of the inverter (a) under voltage condition (b) over voltage condition

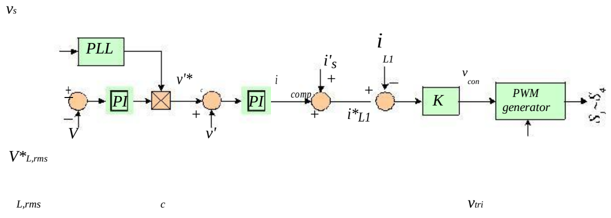
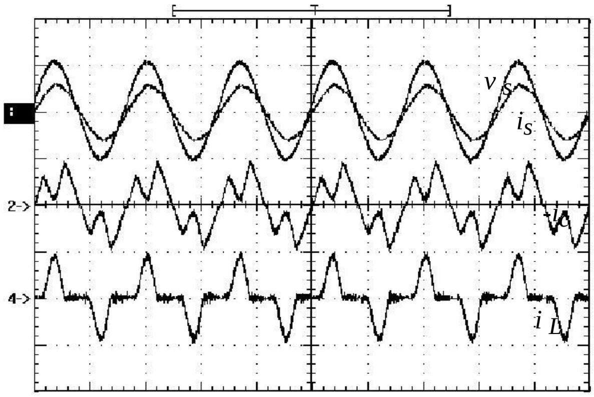
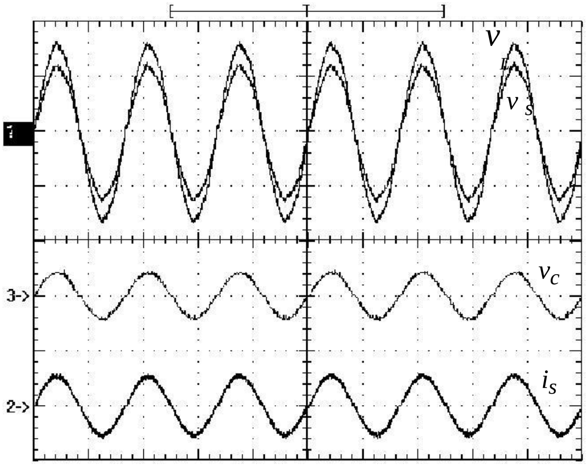


Fig. 8 Control block diagram of the series compensator for load voltage regulation.



(a)



(b)

Fig. 9 Experimental results under the voltage sag condition

(a) source voltage, line current, shunt compensating current and load current (b) source voltage, load voltage, series compensating voltage and line current

[v_S, v_L, v_C: 100V/div; i_s, i_L, i_C: 10A/div; time:10ms/div].

V. EXPERIMENTAL RESULTS

The adopted shunt-series compensator is verified by the experimental results. The source voltage is 110V$_{rms}$/60Hz. The circuit parameters are $L_1=1mH$, $L_2=0.2mH$, $C_1=36\mu F$, and $C=2200\mu F$. The experimental results of the adopted system under the source voltage disturbance and nonlinear load are shown in Figs. 9 and 10. The measured waveforms of the shunt compensator under the voltage sag are given in Fig. 91(a). The shunt compensating current will generate the harmonic and reactive components of load current into the system in order to improve the system power factor. At the same time an active current will be absorbed by the shunt compensator to compensate the dc-link voltage due to the generated in phase series compensating voltage v_C. Fig. 9(b) illustrates the measured waveforms of the series compensator under the voltage sag condition. The in phase compensating voltage v_C will be generated on the out side of the series compensator to make the load voltage at the desired value. Fig. 10 gives the measured waveforms of the shunt-series compensator at the voltage swell and nonlinear load case. The shunt compensator will eliminate the harmonic and reactive currents of the nonlinear load. The series compensator will generate the series compensating voltage that is out of phase of the load voltage to make the load voltage at the desired root mean square voltage.