POWER QUALITY ENHANCEMENT IN AN ISOLATED POWER SYSTEM THROUGH SERIES COMPENSATION

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Abstract – The issue of power quality in an isolated power system is investigated. The use of series compensator (SC) is proposed, not only to mitigate the effect of voltage sag/swell, but also to reduce the distortions due to the presence of non-linear loads in the network. A method of harmonics compensation is described. In the process of the compensation, it is shown that the SC will exchange energy with the external network. It causes undesirable variations in the voltage across the terminals of the SC energy storage system (ESS). A method to maintain the voltage of the ESS is then described. Simulation results verify that the SC is effective in reducing the harmonic distortions and thus improving the supply quality of the isolated power system.

Keywords: isolated power systems, series compensator, harmonics compensation, energy storage system.

1 INTRODUCTION

Despite the coverage of large areas of the developed world by extensive electricity networks, one can still encounter situations where loads are served by relatively small-capacity power systems which are not parts of an interconnected grid network. For instance, such isolated power systems can be found on oil exploration areas and remote mining districts. The isolated power systems are characterized by limited generation capacity and have comparatively low fault level. The electrical source can be in the form of diesel generator-sets and the source impedance is normally high. The loads are often relatively large DC or AC drives. They could contain a significant proportion of variable-speed drives or machinery; these are connected to the generators through power converters [1]. The loads are non-linear and harmonic currents generated by the loads will cause a voltage drop across the source impedance. There is also the occurrence of voltage notches due to momentary short-circuiting of the ac lines during the commutation process of the converters. Thus it can be concluded that the line voltage will contain distortions, the extent of which is likely to be fluctuating as the loads change.

In addition to the industrial drive loads, one can also expect the presence of some low-power sensitive loads such as computers or electronic controllers in the power system. The low-power devices are necessary to ensure the proper functioning of the exploration/mining activities. These loads would be connected in parallel with the nonlinear drive loads. While the total capacity of the sensitive loads can be much smaller than that of the drives or machinery, the distorted line voltage is harmful to the sensitive loads. It could cause the sensitive loads to mal-operate [2]. The loads are also sensitive to short-duration disturbances which appear in the form of voltage-sags or voltage-swells. The disturbances could be due to faults or most likely, the switching on/off of large drive loads. Hence industry standards, such as that described under the ITI curve, have been developed to quantify what would be considered acceptable as power quality for these sensitive loads [3].

While power quality in interconnected systems has attracted much research attention, unfortunately the issue of power quality in isolated power systems has not been so well studied. In [4, 5], the authors propose methods to improve power quality of isolated power systems through flywheel energy storage system and active power filter respectively. These are promising technologies and would find ready applications if they are cost-effective.

An alternative method to improving the power quality of the isolated systems is through the use of series compensators (SC). A SC is viable because it is of smaller capacity compared to a shunt compensator to achieve the same level of voltage quality control. It is based on the well-established voltage-source inverter (VSI) technology. Also, as reported in [6, 7], the SC can function to mitigate the effects of voltage sag/swell although in these previous works, harmonic voltages/current distortions in the networks have been ignored. With the SC so installed in an isolated power system, the present investigation is to explore the technique by which the compensator role can be extended to include that of the mitigation of harmonics.

2 SYSTEM MODEL

The simple isolated power system model shown in Fig. 1 is used to explain the principle of the proposed harmonics compensation method of the SC. The upstream generators are represented as an ideal voltage source and Z_S represents the equivalent source impedance. The main drives or machinery loads are modeled as a lumped resistance-inductance load connected to the source through a power converter which is assumed to be an uncontrolled six-pulse rectifier in this study. The much smaller-capacity sensitive loads are assumed supplied through a separate feeder. Often, such critical or sensitive loads such as PC and control devices contain input rectifiers that are capacitive in nature. Although these loads could also be non-linear, however, their combined capacity is small compared to the main rectifier loads. Hence, the sensitive loads are assumed to be linear as their contributions towards the distortions in V_L is negligible. In the investigation, the load is modeled by a resistance R in parallel with a capacitor C. The value of R will be obtained based on the real power drawn by the sensitive load at the voltage $V_L^{\prime}$. C can be obtained from the data supplied by the rectifier manufacture.

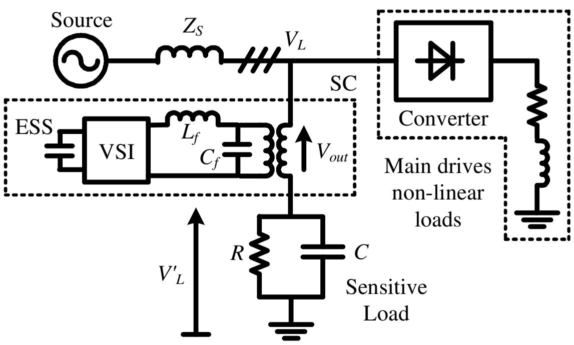


Fig.1 A typical isolated power system with SC

The series compensator (SC) is connected upstream of the sensitive load through an injection transformer. It is series connected with the sensitive load and its function is to ensure that the voltage across the load terminals is of high quality. The central part of the SC is the VSI and an energy storage system (ESS). PWM switching scheme is often used in the VSI. Due to the switching, harmonics are generated and filtering is required. L_f and C_f are the filter inductance and capacitance. While the detailed function of the SC under a voltage-sag can be found in [6], it is suffice to state that the VSI synthesizes the required voltage quantity (V_{out}) which would be injected in series with $V_L^{\prime}$. The ESS would act as a buffer and provides the energy needed for load ride-through during a voltage-sag. Conversely, during a voltage-swell, excess energy from the network would be stored in the SC so that $V_L^{\prime}$ can be controlled.

Under steady-state conditions, harmonic currents generated by the main nonlinear converter-drive load will cause a voltage drop across Z_s. Thus it results in distortions in the line voltage V_L: V_L consists of the fundamental and harmonic voltage components.

3 HARMONIC MITIGATION

3.1 Principle of harmonics compensation

The underlying principle when the SC is used to compensate for upstream voltage sag/swell has been discussed in [6, 7]. In Fig. 1, distorted voltage V_L will appear on the upstream source-side of the sensitive load and the phase voltages can be expressed as

$$V_{La}(t)=\sum_{n=1}^{\infty}[V_{0n}+V_{1n}\sin(n\omega t+\varphi_{1n})+V_{2n}\sin(n\omega t+\varphi_{2n})] \quad (1)$$

$$V_{Lb}(t)=\sum_{n=1}^{\infty}[V_{0n}+V_{1n}\sin(n\omega t+\varphi_{1n}-2n\pi/3) +V_{2n}\sin(n\omega t+\varphi_{2n}+2n\pi/3)] \quad (2)$$

$$V_{Lc}(t)=\sum_{n=1}^{\infty}[V_{0n}+V_{1n}\sin(n\omega t+\varphi_{1n}+2n\pi/3) +V_{2n}\sin(n\omega t+\varphi_{2n}-2n\pi/3)] \quad (3)$$

where n is the harmonic order; V_{0n} is the zero phase sequence voltage component; V_{1n} and φ_{1n} are the magnitude and phase of the positive phase sequence voltage components; V_{2n} and φ_{2n} are the magnitude and phase of the negative phase sequence voltage components. Clearly, the distorted voltage is undesirable at the sensitive load terminals. The desirable terminal voltage for the sensitive load is the fundamental components of the voltages contained in (1)-(3), i.e.

$$V_{la}(t)=V_{11}\sin(\omega t+\varphi_{11}) \quad (4)$$

$$V_{lb}(t)=V_{11}\sin(\omega t-2\pi/3+\varphi_{11}) \quad (5)$$

$$V_{lc}(t)=V_{11}\sin(\omega t+2\pi/3+\varphi_{11}) \quad (6)$$

The proposed voltage injection method is to compensate for the difference between V_L and the desired voltage described by (4)-(6). This is achieved by injecting an ac voltage component in series with the incoming three-phase network. Hence from (1)-(6), the desired injection voltages are

$$V_{inja}(t)=V_{la}(t)-V_{La}(t)=\sum_{n=1}^{\infty}V_{0n}-\sum_{n=2}^{\infty}V_{1n}\sin(n\omega t+\varphi_{1n}) -\sum_{n=1}^{\infty}V_{2n}\sin(n\omega t+\varphi_{2n}) \quad (7)$$

$$V_{injb}(t)=V_{lb}(t)-V_{Lb}(t)=\sum_{n=1}^{\infty}V_{0n}-\sum_{n=2}^{\infty}V_{1n}\sin(\omega t+\varphi_{1n}+2\pi/3) -\sum_{n=1}^{\infty}V_{2n}\sin(n\omega t+\varphi_{2n}+2n\pi/3) \quad (8)$$

$$V_{injc}(t)=V_{lc}(t)-V_{Lc}(t)=\sum_{n=1}^{\infty}V_{0n}-\sum_{n=2}^{\infty}V_{1n}\sin(\omega t+\varphi_{1n}-2\pi/3) -\sum_{n=1}^{\infty}V_{2n}\sin(n\omega t+\varphi_{2n}-2n\pi/3) \quad (9)$$

The above equations can be written in a compact form. From (4)-(6), define $\vec{V}_{Lf}=[V_{la}(t),V_{lb}(t),V_{lc}(t)]^T$ and from (1)-(3), denote $\vec{V}_L=[V_{La}(t),V_{Lb}(t),V_{Lc}(t)]^T$. Let $\vec{V}_{Lh}$ be the vector containing all the harmonic components in (1)-(3). Hence, from (7)-(9), the injection voltage of the SC would be

$$\vec{V}^*=\vec{V}_{Lf}-\vec{V}_L=-\vec{V}_{Lh} \quad (10)$$

$\vec{V}_L$ can be measured online and its fundamental voltage $\vec{V}_{Lf}$ can be obtained using, for example, a Phase Locked Loop (PLL) scheme. Hence the injection voltage

$\vec{V}^*$ can be generated online and used to mitigate the harmonic distortions in the manner described below.

3.2 A Possible Mitigation Method

Fig. 2 shows a typical scheme whereby the SC, through the injection of the voltage V_{out}, compensates for the harmonic voltage. In this study, the resistance and leakage inductance of injection transformer is assumed negligible. The transformer turns-ratio is 1:n. Only the network branch pertaining to the sensitive load is included. The distorted source-side voltage V_L is represented as a harmonic voltage source. Z_{Load} denotes the parallel RC load shown in Fig. 1 and the load terminal voltage is V'_L. The corresponding line current is I_{Load}.

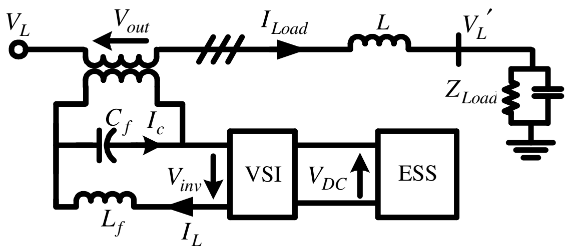


Fig. 2. Schematic diagram showing the interconnection of the SC with the sensitive load.

The block diagram of the control scheme for a conventional SC designed for load ride-through enhancement function during a voltage-sag is given in Fig. 3 [7]. As an initial attempt, the same scheme may be considered for adoption herewith for the purpose of mitigating harmonic distortions. In this scheme, the injection voltage V_{out} is regulated to follow the reference voltage V^* which is described by (10). Thus it requires V_{out} to be compared with V^*. The error is multiplied by the voltage error feedback gain K_2C_f and fed to the second stage as the reference for the inductor current. This virtual inductor current reference is compared with the actual inductor current and the error is multiplied with the current error gain K_1L_f to form the inner feedback loop. The resulting quantity of this loop is subsequently fed to the PWM generator of the inverter.

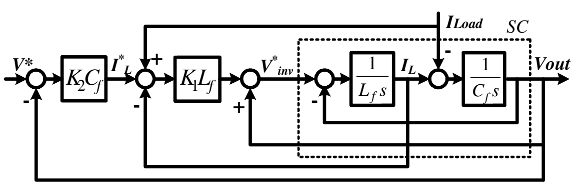


Fig. 3 Closed-loop control scheme for the SC

The load current I_{Load} is considered a disturbance caused by sensitive load changes. The effect of I_{Load} on the harmonic distortions is not the main concern in the design of this controller. Rather, the focus is on the control of V_{out} to track V^*, due to the distortions caused by the upstream main loads. For this purpose, the closed-loop transfer function between V_{out} and V^* can be shown as:

$$G_{cl}(s) = \left.\frac{V_{out}}{V^*}\right]_{I_{Load}=0} = \frac{K_1K_2}{s^2 + K_1 s + K_1K_2} \tag{11}$$

From Fig. 3, therefore V_{out} can be expressed as

$$V_{out}(s) = G_{cl}(s)V^*(s) + Z(s)I_{Load}(s) \tag{12}$$

where $$Z(s) = -\frac{s}{s^2 + K_1 s + K_1K_2}\cdot\frac{1}{C_f}$$

$Z(s)$ is the equivalent impedance of the SC, while $G_{cl}(s)$ is as given by (11). $G_{cl}(s)$ is a second-order system; therefore, the damping ratio and the un-damped natural frequency of the SC control system are given as

$$\xi = 0.5\sqrt{K_1/K_2} \tag{13}$$

$$\omega_n = \sqrt{K_1K_2} \tag{14}$$

In order to obtain a critically damped response, ξ=1 and this can be achieved when

$$K_2 = K_1/4 \tag{15}$$

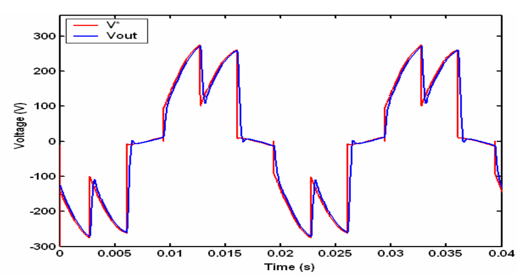
Substituting (15) into (11), $G_{cl}(s)$ can be rewritten as

$$G_{cl}(s) = 1\Big/\left(1+\frac{s}{K_1/2}\right)^2 \tag{16}$$

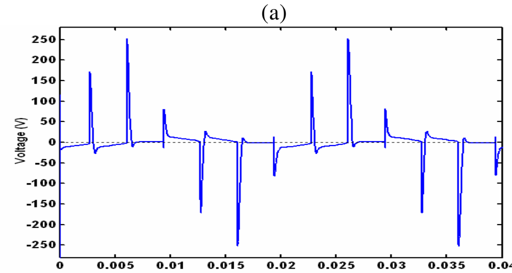
For most systems, there is an upper limit on the proportional feedback gain in order to achieve a well-damped stable response. Thus, K_1 and K_2 should be selected with this consideration in mind.

3.3 Improvements needed

As stated, the reference voltage (V^*) of the control system can be obtained according to (10). Due to the effect of commutation, V^* consists of six segments per cycle. By adopting the control scheme shown in Fig. 3, typical waveforms of V^* and V_{out} of the SC are as shown in Fig. 4 (a). As the SC has a finite bandwidth, a phase lag would be introduced into the control system. Hence it explains the observation that V_{out} lags V^*. As a consequence, large voltage pulses appear in the difference between the two voltages at the beginning of each segment. The difference is shown in Fig. 4 (b). Obviously a more detailed analysis of the controller scheme is called for because the large voltage errors are detrimental to the satisfactory performance of the power system.



(a)



(b)

Fig. 4(a) Waveforms of V^* and V_{out} of SC; (b) Difference between V^* and V_{out}

The difference in the voltages can be 'modeled' approximately as a train of square waves, with six pulses appearing per cycle. Notice that the RC sensitive load impedance decreases rapidly at high frequency, as shown in Fig. 5. As a result, the voltage pulses will cause large harmonic current distortions to appear in I_{Load}. The distortions have to be mitigated to protect the sensitive load.

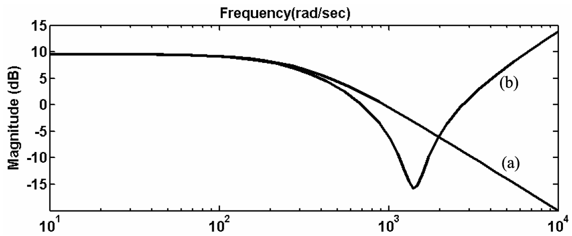


Fig.5 A typical frequency response characteristic (a) the RC load and (b) the combined filter L and RC load.

Limited by the finite bandwidth of the SC, the high-frequency components of I_{Load} cannot be effectively eliminated solely by controlling the SC itself through the controller shown in Fig. 3. It is proposed that an inductive filter L be installed between the SC and the sensitive load, as shown in Fig. 2. L can act as a low-pass filter to eliminate the high-frequency component of I_{Load}. However the presence of L could cause fundamental voltage regulation problem. Additional consideration has to be taken and this will be dealt with in Section 4.

With L in place, only the square wave voltage component shown in Fig. 4(b) will appear across the sensitive load terminals, as the high-frequency component have been filtered off. During commutation the reference voltage is a sine function [8], the slope of which could be obtained. For an uncontrolled six-pulse rectifier, each diode conducts for 120° which results in the waveform V^* as shown in Fig.4 (a). Also the duty cycle of the square wave is 2/3 and from the series compensator transfer function, the time lag in the SC system can be determined [9]. The magnitude of the square wave can therefore be estimated using the slope and the time lag. The voltage harmonic components of the square wave can be obtained through Fourier analysis. This will provide the necessary information to generate the additional harmonic voltage, to be injected by the SC into the circuit. The injection will therefore comprise of the harmonics of the pulse waveform.

The RMS value of the final harmonic current can be determined (or at least approximated), using the voltage harmonics determined earlier and applied across the impedance of the circuit external to the SC. Thus, the aim would then be to design the impedance for the external circuit to meet a certain criteria: i.e. to limit the total harmonic distortion (THD) in I_{Load}.

4 PROPOSED DESIGN

With the filter L included, the impedance of the combined RC load and L will increase at high frequencies. However, a resonance will occur due to the combination of L and C in the circuit, as shown in Fig. 5. This is a concern because any harmonic voltage close to the resonant frequency will result in large resonant current. To overcome this problem, one possibility is to introduce a damping resistor into the circuit but the increase in loss does not make it an attractive proposition. Instead, a method to control the equivalent impedance (Z) included in (12) is proposed herewith. The technique would produce the same effect as that of the damping resistor but without causing increased losses.

Suppose Z is adjusted by an amount $\Delta Z(s)$. Then from (12) the resulting output voltage of the SC is

$$V_{out}(s) = G_{cl}(s)[V^*(s) + R'(s)I_{load}(s)] + Z(s)I_{load}(s) \quad (17)$$

where the function $R'(s) = \Delta Z(s)/G_{cl}(s)$.

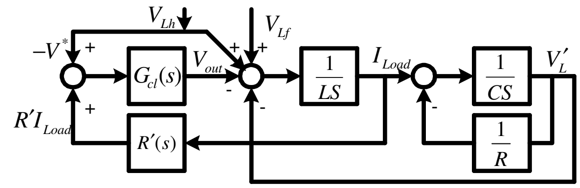


Fig. 6 Block diagram of the SC-sensitive load with load current feedback.

The block diagram of the L-RC branch with the SC is re-drawn, as shown in Fig. 6, but with the load current feedback. Source-side voltage (V_L) consists of the fundamental voltage V_{Lf} and the harmonics voltage V_{Lh}. From previous Section, (10) shows that V_{Lh} is the reference voltage V^* to be injected into the system. G_{cl}(s) is the transfer function defined by (11). From (17), it can be seen that V^* will now become $V^*(s)+R'(s)I_{Load}(s)$. $R'(s)I_{Load}(s)$ can be readily implemented since I_{Load} is measurable and can be used in the feedback scheme.

In the proposed method, $R'(s)$ is designed as a lead-lag filter of the form $(s+\omega_1)/(s+\omega_2)$ and has the typical frequency response characteristic shown in Fig. 7. Thus $R'(s)$ appears as high impedance for high frequency current components while the fundamental frequency component in I_{Load} will not be affected.

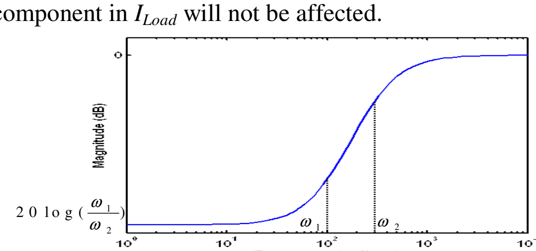


Fig. 7 Frequency response characteristic of $R'(s)$

With $R'(s)$ in place, the total impedance of the sensitive load branch is now modified to become

$$Z'(s) = L(s) + R'(s)G_{cl}(s) + Z(s) \quad (18)$$

where $L(s)$ is the impedance of the inductive filter.

The voltage drop term $[L+R'(s)G_{cl}(s)]I_{Load}$ at the fundamental frequency ω will have to be controlled to satisfy prescribed voltage regulation requirement. Suppose the sensitive load terminal voltage is to be at least V_{min} p.u. Then it can be shown that the following voltage regulation constraint has to be met:

$$\left|L+R'(j\omega)\cdot G_{cl}(j\omega)\right|\cdot\left|I_{Load}\right|<$$
$$(1-V_{\min})\left|Z_{Load,fullload}(j\omega)\right|\cdot\left|I_{Load}\right| \quad (19)$$

$Z_{Load,\,fullload}(j\omega)$ is the impedance of the sensitive load under the full load condition.

From (11), it can be seen that $G_{cl}(j\omega)$ is close to unity at ω as V_{out} has to track V^*. Then (19) reduces to

$$\left|L+R'(j\omega)\right|<(1-V_{\min})\left|Z_{Load,fullload}(j\omega)\right| \quad (20)$$

This places a constraint on the choice of L and $R(s)$.

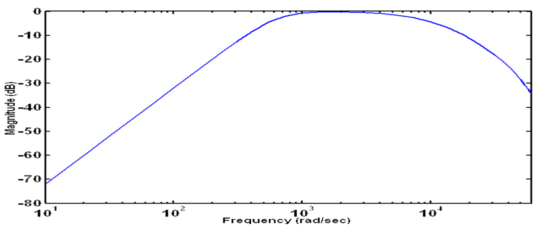


Fig. 8. A typical frequency response characteristics of $R'(s)\cdot G_{cl}(s)$

To limit the high-frequency harmonics, one also has to maximize the total branch impedance Z' described by (18) at high frequency. The variables in this design are L and $R'(s)G_{cl}(s)$. Note that for $R'(s)$ to assume the form of a lead-lag filter with two cutoff frequencies ω_1, ω_2, the difference in the magnitude of $R'(s)$ at low frequency and that at high frequency is governed by the ratio ω_1/ω_2, as shown in Fig. 7. It is desirable for $R'(s)$ to be small at low frequencies such that it does not cause excessive voltage drop across the SC terminals. So if ω_2 can be pushed higher, the low frequency impedance due to $R'(s)$ can then be reduced. Limited by the bandwidth of $G_{cl}(s)$, $R'(s)G_{cl}(s)$ assumes high impedance value over a range of frequencies as shown in Fig. 8. If the series resonant frequency happens to fall within this frequency range, the possibility of having large current at the resonant frequency is removed. Beyond this frequency band, the contribution of L in providing the high frequency impedance into the branch comes into effect. The frequency response characteristics of the branch impedance will then assume the form shown in Fig. 9.

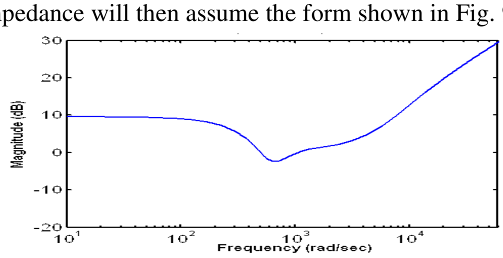


Fig. 9. A typical frequency response characteristics of $Z'(s)$

5 CONTROL OF VOLTAGE IN THE ENERGY STORAGE SYSTEM

For the convenience of analysis and to avoid complicated mathematical expressions, a single-phase equivalent system is used to describe the three-phase system shown in Fig. 2. If the function of the SC is solely for the purpose of harmonics compensation, the instantaneous power at the SC output will be of the form

$$p(t)=V_{Lh}(t)I_{Load}(t)=\sum_{k=2}^{\infty}V_k\sin(k\omega t+\varphi_k)\sum_{k=1}^{\infty}I_k\sin(k\omega t+\theta_k) \quad (21)$$

The average power is

$$P=\frac{1}{2}\sum_{k=2}^{\infty}V_kI_k\cos\phi_k \quad (22)$$

where $\phi_k=\varphi_k-\theta_k$ .Note that only power components associated with the harmonics are contained in P.

P is either imported into or exported from the SC to the external system. The losses in the VSI would be low and can be ignored. Hence the energy exchange between the SC and the external power system is

$$E=\frac{T}{2}\sum_{k=2}^{\infty}V_kI_k\cos\phi_k \quad (23)$$

over the time interval T. The SC supplies energy to the external system when $E\le 0$. As the only significant source of energy storage in the SC is the ESS, the export of the energy to the external system will result in a decrease in the voltage V_{DC}. Conversely V_{DC} will rise when $E\ge 0$. Variation of V_{DC} will affect the compensation capability of the SC and excessive voltage rise will damage the ESS. Hence V_{DC} has to be controlled within certain range.

In order to achieve this, there must be control on the energy flow. This can be achieved by adjusting the phase of the fundamental component of the reference voltage of the SC. If a phase shift α is introduced to the reference voltage for, say phase "a" of (4), one obtains

$$v'_L(t)=V_1\sin(\omega t+\varphi_1+\alpha) \quad (24)$$

Since only the fundamental voltage component is involved in the phase shift, the second subscript "1" in (4) has been omitted in (24). Furthermore, notice that the intention is not to change the magnitude of the fundamental component of the load-side voltage V'_L. Hence v'_L has the same magnitude as without the phase shift. With an assumed constant impedance load model, I_1 will also remain constant following the phase shift.

It then follows that the new injection voltage is

$$v_{inj}(t)=V_1\sin(\omega t+\varphi_1+\alpha)-V_1\sin(\omega t+\varphi_1)-V_{Lh} \quad (25)$$

Refer to (22) and (23), the energy flow between the ESS and the external power system now becomes

$$E=\frac{T}{2}(V_1I_1\cos(\phi_1+\alpha)-\sum_{k=2}^{\infty}V_kI_k\cos\phi_k) \quad (26)$$

From (26), it can be seen that E could be forced to be zero if α is selected to be α_0 where

$$\alpha_0=\arccos(\frac{1}{V_1I_1}\sum_{k=2}^{\infty}V_kI_k\cos\phi_k)-\phi_1 \quad (27)$$

So by the appropriate selection of the phase shift α in the fundamental component of V_{inj}, E and therefore V_{DC} can be controlled. In the proposed method, V_{DC} is monitored: if the voltage starts to decrease, it shows that there is a net energy flow from the SC to the external system. The SC should start to absorb energy from the external system to increase V_{DC}. Conversely if V_{DC} rises, the SC should inject energy to the external system. The injection or absorption of energy is through the adjustments in α.

Based on the above principle, the control strategy of α for different load conditions can be obtained. With the assumption of constant load power factor, the phasor diagram is shown in Fig. 10. $\vec{V}_{Lf}$ is the fundamental source-side voltage. $\vec{V}'_{Lf}$ is the load-side voltage after the phase shift. $\vec{V}^*$ is the injection voltage (also the reference voltage) and $\vec{I}_{Load}$ is the sensitive load current. θ is the load power factor angle. β is the phase difference between $\vec{V}^*$ and $\vec{I}_{Load}$. As only the phase shift is introduced, the loci of $\vec{V}_{Lf}$ and $\vec{V}'_{Lf}$ will lie on a circle with radius V_l.

From Fig. 10, it can be seen that

$$\beta = 90^o + \theta - \alpha/2 \tag{28}$$

Therefore, the active power flow between the SC and the external system is

$$P = |\vec{V}^*||\vec{I}_{Load}|\cos\beta \tag{29}$$

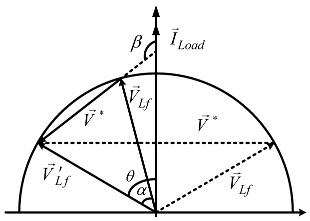


Fig.10 Phasor diagram showing voltage injection for a lagging power factor load.

Clearly when $\beta > 90^o$, $P < 0$, the SC absorbs energy from the external system. From (29), therefore, α should be adjusted such that $0^o < \alpha < 2\theta$. Energy will be imported into the SC and V_{DC} will increase. When $\alpha = 2\theta$, $\vec{V}^*$ is then perpendicular to I_{Load}. It means that P is zero. This condition is shown by the dotted lines in Fig. 10.

Conversely, for the SC to export energy to the external system, α should be within the range 2θ - 360° < α < 0°. A decrease in V_{DC} will be observed.

The above analysis can be summarized in Table I, which shows how regulating V_{DC} for lagging and leading load power factor conditions can be achieved through the adjustments in phase shift α.

TABLE I

Load power factor	$0 < \alpha < 2\theta$	$2\theta\text{-}360^o < \alpha < 0$
Lagging: $0 \le \theta \le \pi/2$	V_{DC} increase	V_{DC} decrease
Leading: $-\pi/2 \le \theta \le 0$	V_{DC} decrease	V_{DC} increase

From the above analysis, it is clear that in order to limit the variations in V_{DC}, a phase shift between the source-side fundamental voltage $\vec{V}_{Lf}$ and the compensated load-side voltage $\vec{V}'_{Lf}$ is called for. The method of progressive phase shift similar to that described in [6] can be adopted. V_{DC} is continuously monitored and as soon as it is outside a set range, adjust α in the manner based on Table I until the voltage is within the set range.

6 ILLUSTRATIVE EXAMPLE

The example of Fig. 2 is used to verify the effectiveness of the SC and its control strategy. The corresponding parametric values used are given in Table II and the simulations were accomplished using MATLAB. The capacity of the isolated system is assumed to be 1.5MVA, a typical level seen in practice. The source is assumed to have a reactance value of 1 p.u. The main load is assumed to be a six-pulse rectifier and is nominally at 1 MVA and that of the sensitive load is at 0.05MVA. The injection transformer is assumed to have a turns-ratio of 1:1. This is a reasonable assumption as the focus of the study is to demonstrate the principle of operation of the SC and not on the detailed design of the compensator. As the switching frequency of the VSI was chosen to be 20 kHz, the controller was based on the setting of ξ =1 and ω_n = 2π·500 rad/sec. Thus K_1 =2π·1000 and K_2 =2π·250 were determined.

TABLE II SYSTEM PARAMETERS

Parameters	Values used in the simulation model
Source capacity	1.5MVA
Source reactance	1 p.u.
Sensitive load capacity	0.05 MVA
Injection transformer turn ratio	1:1

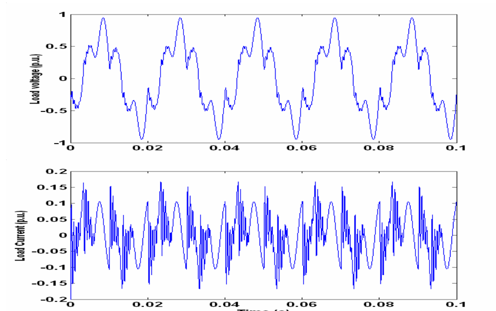


Fig. 11 Terminal voltage and current drawn by the sensitive load: without SC

Fig. 11 shows the waveforms of V_l and I_{Load} without the SC. It can be shown that V_l has a THD level of 37%. I_{Load} has a large harmonic content; its THD is 180%.

Fig. 12 shows the corresponding waveforms when the SC is in service. With harmonics compensation by the SC, the sensitive load is protected against the distortion introduced by the main drive load and the THD of the current has been significantly reduced to 6%.

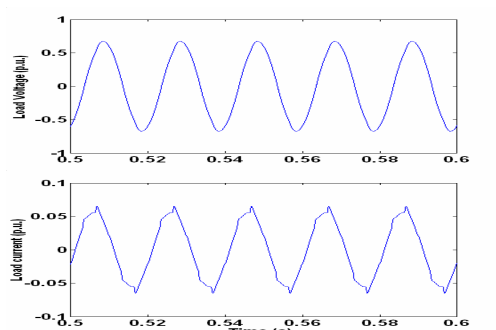


Fig. 13 Terminal voltage and current drawn by the sensitive load: with SC

Fig. 13 shows the voltage across the ESS but without phase shifting of the fundamental component of the reference voltage. It is shown that the voltage across the ESS decreases during injection, which means that the SC injects power to the external system. This is obviously un-sustainable for the continuous operations of the SC.

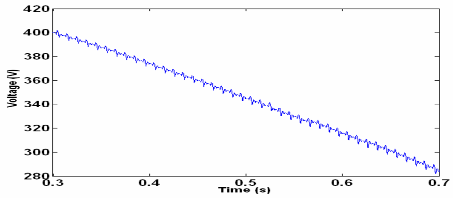


Fig. 13 Terminal voltage of ESS without phase shift in the reference voltage

Fig. 14 shows the voltage of the ESS but with the proposed phase shifting of the fundamental component of the reference voltage. It shows that the voltage can be restored to its nominal level. Therefore the strategy can be applied for continuous operation of the power system. Indeed, in this study, a change in the main drive load from 1MVA to 1.1MVA has been introduced at t = 0.7 s. This is in order to assess how the SC would response to the load change. It seems that the technique is again effective in maintaining the voltage of the ESS. Fig. 15 shows the corresponding sensitive load terminal voltage and current, with the phase shift. THD are 1% and 9% for the voltage and current respectively.

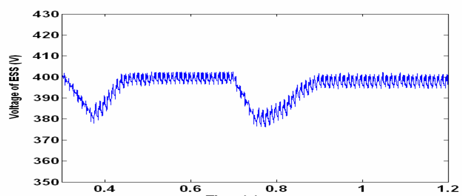


Fig.14 Terminal voltage of ESS with phase shift in the reference voltage

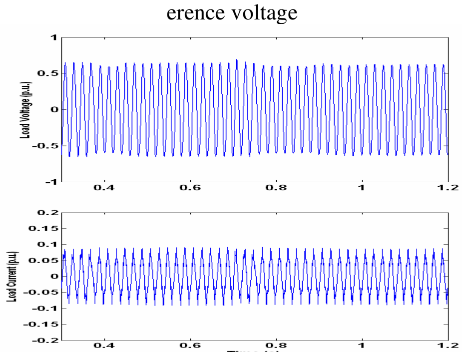


Fig. 15 Sensitive load terminal voltage and current

7 CONCLUSIONS

Power quality improvement in an isolated power system through series compensation has been investigated. A method to control the SC so that it can compensate for the harmonics under steady-state condition has been proposed. The proposed method is based on the control of the SC branch impedance. A feedback scheme is introduced through the control system of the SC. This is coupled with an inductive filter intended for mitigating high-order harmonic currents. In the process of harmonic voltage compensation, power exchange exists between the SC and the external network. It would result in the variation of the terminal voltage of the energy storage system of the SC. A method to maintain the voltage of the ESS through the phase shifting of the fundamental component of the reference voltage has been described. The effectiveness of the proposed method has been verified through simulation.

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