Power Quality Enhancement in an Isolated Power System Using Series Compensation

[1]Harinath Saggu, [2]Ch. Nagalaxmi, [3]V. K. R. Mohan Rao
[1]PG Scholar, [2]Assistant Professor, [3]Associate Professor, [1, 2, 3] Holy Mary Institute of Technology & Science

ABSTRACT: *In Isolated power systems the power quality problem is compounded as the drive converter loads are likely to fluctuate in conjunction with mining or exploration areas. The use of compensators in improving power quality of isolated power systems is considered. The roles of the compensators are to mitigate the effects of momentary voltage sags/swells, and to control the level of harmonic distortions in the networks. A control strategy for both series compensator and shunt compensator is developed to regulate power flow. However series compensator reduces harmonics to an acceptable level when compared to shunt compensator. This is achieved through phase adjustment of load terminal voltage. It leads through an increase in ride through capability of loads to the voltage sags/swells. Validity of the technique is illustrated through simulation. Hence series compensator with LC Filter is used in reducing the harmonic distortions in isolated power systems.*

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

I. INTRODUCTION

The typical definition for a harmonic is a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Some references [1-2] refer to clean or pure power as those without any harmonics. Harmonics have been around for a long time and will continue to do so [3-5] with effects like:

- Overheated transformers, especially delta windings where triplen harmonics generated on the load side of a delta-wye transformer will circulate in the primary side.
- Nuisance operation of protective devices, including false tripping of relays and failure of a UPS to transfer properly, especially if controls incorporate zero-crossing sensing circuits.
- Bearing failure from shaft currents through uninsulated bearings of electric motors.
- Blown-fuses on PF correction caps, due to high voltage and currents from resonance with line impedance.
- Mis-operation or failure of electronic equipment
- If there are voltage subharmonics in the range of 1-30Hz, the effect on lighting is called flicker. This is especially true at 8.8Hz, where the human eye is most sensitive, and just 0.5% variation in the voltage is noticeable with some types of lighting.

The sensitive loads would be connected in parallel with the nonlinear drive. Often such sensitive loads also contain input rectifiers that are capacitive in nature. The combined sensitive loads may be represented by the parallel RC circuit shown in Fig. 1. While the total capacity of the sensitive loads could be much smaller than that of the main drives, the distorted supply voltage is harmful to the sensitive loads. Excessive voltage distortions could cause the sensitive loads to mal-operate. The loads are also sensitive to short-duration disturbances in the form of voltage sags or swells. The disturbances can be due to faults or most likely, the fluctuating load cycles of the main drives. In the latter case, voltage flickers can occur and they can be of major concern. Thus one important consideration in the design and operation of the power system would be to ensure that the quality of supply to the sensitive loads comply with that prescribed under industry standards, such as the ITI curve [3].A traditional method to achieve improved PQis to use passive filters connected at the sensitive load terminals [4]. However, this practice has some shortcomings: the effectiveness of the scheme could deteriorate as the source impedance or load condition changes; it can lead to resonance between the filter and the source impedance. For these reasons, active filters such as that described in [5] may be used. Essentially an active filter, connected at the sensitive load terminal, injects harmonic currents of the same magnitude but of opposite polarity to cancel the harmonics present there. However, as noted earlier, harmonic distortions are only part of the problem faced in such a network: the variations in the drive load would result in voltage sag/swell or flickers appearing in the upstream voltage. Thus, the challenge is to regulate the sensitive load terminal voltage so that its magnitude remains constant and any harmonic distortion is reduced to an acceptable level. In a recent study, [6] proposes a series compensation method to mitigate the harmonics problem for the power system shown in Fig. 1. However, compensation for voltage sag/swell or flicker has not been considered. Series voltage compensation methods have been discussed in [7], [8] for the mitigation of short-duration voltages/swells but the presence of harmonic voltages/current in the networks has been ignored. This paper intends to fill this gap. Specifically, the investigation is to develop a method to control the fundamental component of . The control is achieved by regulating power flow via phase angle adjustment. Unlike the previous methods of [6]–[8], the investigation also shows that the voltage-sag ride through capability of the sensitive load can be improved through importing harmonic power from the external system into the SC.

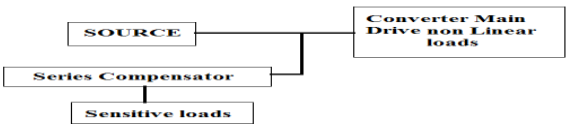

Fig.1 Typical isolated power system installed with a Series compensators.

II. HARMONIC MITIGATION AND POWER FLOW IN ISOLATED POWER SYSTEM

The simple isolated power system model shown in Fig. 2 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 *ZS* 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' . *C* can be obtained from the data supplied by the rectifier manufacture.

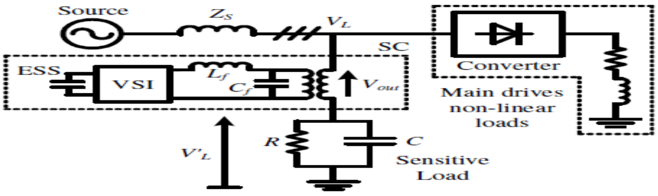

Fig.2 A typical isolated power system with SC

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 [8], it is suffice to state that the VSI synthesizes the required voltage quantity (*Vout*) which would be injected in series with V_L'. 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' can be controlled.

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

A. Principle of harmonics compensation

The underlying principle when the SC is used to compensate for upstream voltage sag/swell has been discussed in [8,9]. In Fig. 2, distorted voltage V_L will appear on the upstream source-side of the sensitive load and the phase voltages can be expressed as

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

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

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

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.

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

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

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

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

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

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

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

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 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

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

$\vec{V}_L$ 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.

B. Possible Mitigation Method

Fig. 3 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. 2 and the load terminal voltage is V'_L. The corresponding line current is *ILoad*.

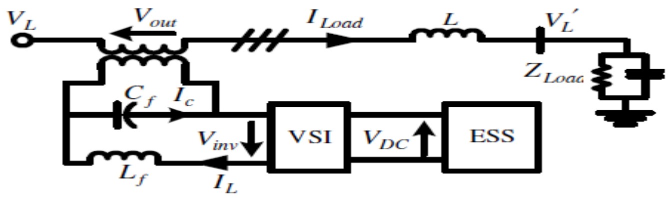

Fig. 3. Schematic diagram showing the interconnection of the SC with the sensitive load

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. 4. 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 *Vout* 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_{2Cf} 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_{1Lf} to form the inner feedback loop. The resulting quantity of this loop is subsequently fed to the PWM generator of the inverter.

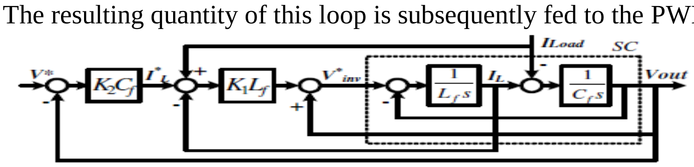

Fig. 4 Closed-loop control scheme for the SC

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:

$$G_{cl}(s) = \left.\frac{V_{out}}{V^*}\right]_{I_{Load}=0} = \frac{K_1 K_2}{s^2 + K_1 s + K_1 K_2} \qquad (11)$$

From Fig. 4, therefore V_{out} can be expressed as

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

Where

$$Z(s) = -\frac{s}{s^2 + K_1 s + K_1 K_2}\cdot\frac{1}{C_f}$$

$Z(s)$ 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

$$\xi = 0.5\sqrt{K_1/K_2} \quad (13)$$

$$\omega_n = \sqrt{K_1 K_2} \quad (14)$$

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

$$K_2 = K_1/4 \quad (15)$$

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

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

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

III. 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. 3. 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

$$p(t) = V_{Lh}(t) I_{Load}(t) = \sum_{k=2}^{\infty} V_k \sin(k\omega t + \varphi_k) \sum_{k=1}^{\infty} I_k \sin(k\omega t + \theta_k) \quad (17)$$

The average power is

$$P = \frac{1}{2}\sum_{k=2}^{\infty} V_k I_k \cos\phi_k \quad (18)$$

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

$$E = \frac{T}{2}\sum_{k=2}^{\infty} V_k I_k \cos\phi_k \quad (19)$$

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 *VDC*. Conversely *VDC* 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 is introduced to the reference voltage for, say phase “a” of (4), one obtains

$$v'_L(t) = V_1 \sin(\omega t + \varphi_1 + \alpha) \quad (20)$$

Since only the fundamental voltage component is involved in the phase shift, the second subscript “1” in (4) has been omitted in (20). 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

$$v_{inj}(t) = V_1 \sin(\omega t + \varphi_1 + \alpha) - V_1 \sin(\omega t + \varphi_1) - V_{Lh} \quad (21)$$

Refer to (18) and (19), the energy flow between the ESS and the external power system now becomes

$$E = \frac{T}{2}(V_1 I_1 \cos(\phi_1 + \alpha) - \sum_{k=2}^{\infty} V_k I_k \cos\phi_k) \quad (22)$$

From (22), it can be seen that E could be forced to be zero if α is selected to be α_0 where

$$\alpha_0 = \arccos(\frac{1}{V_1 I_1}\sum_{k=2}^{\infty} V_k I_k \cos\phi_k) - \phi_1 \quad (23)$$

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. 5. $\vec{V}_{Lf}$ 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. βis 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 *V1*.
From Fig. 5, it can be seen that

$$\beta = 90^{o} + \theta - \alpha/2 \qquad (23)$$

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

$$P = \left|\bar{V}^{*}\right|\left|\bar{I}_{Load}\right| \cos\beta \qquad (24)$$

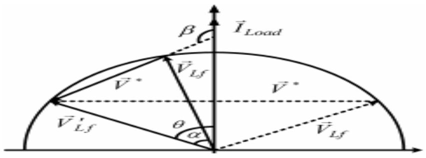

Fig.5 Phasor diagram showing voltage injection for a lagging power factor load.

Clearly when β > *90º*, *P < 0*, the SC absorbs energy from the external system. From (29), therefore, α should be adjusted such that 0º <α < 2θ . Energy will be imported into the SC and V_{DC} will increase. When α = 2θ , $V*$ is then perpendicular to *ILoad*. It means that *P* is zero. This condition is shown by the dotted lines in Fig. 5. 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 < α < 2θ*	*2θ-360º < α <0*
Lagging: 0 ≤ θ ≤ π/2	V_{DC} increase	V_{DC} decrease
Leading:- π/2 ≤ θ ≤ 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.

IV. 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 *K1* =2π·1000 and *K2* =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

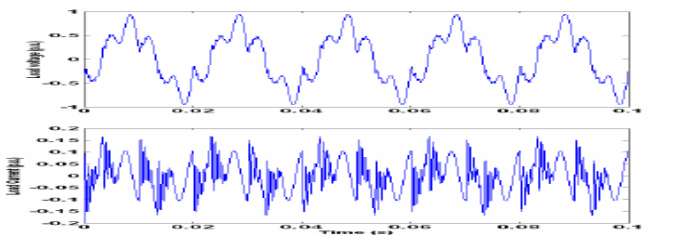

Fig. 6 Terminal voltage and current drawn by the sensitive load: without SC

Fig. 6 shows the waveforms of V_l and $_{ILoad}$ 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. 7 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%.

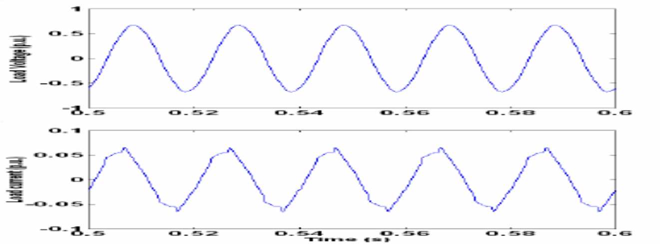

Fig. 7 Terminal voltage and current drawn by the sensitive load: with SC

Fig. 8 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.

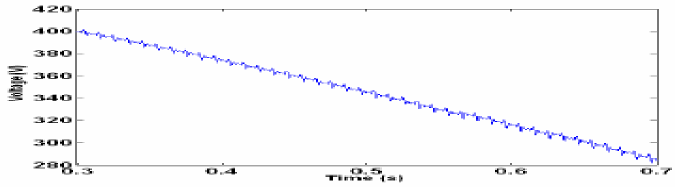

Fig. 8 Terminal voltage of ESS without phase shift in the reference voltage

Fig. 9shows 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.

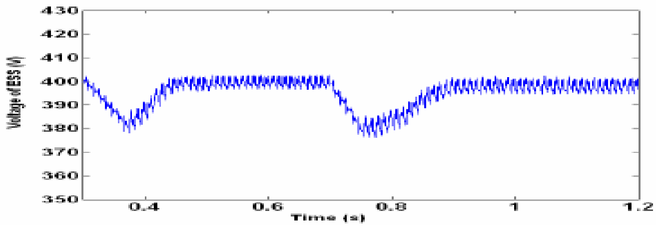

Fig.9 Terminal voltage of ESS with phase shift in the reference Voltage

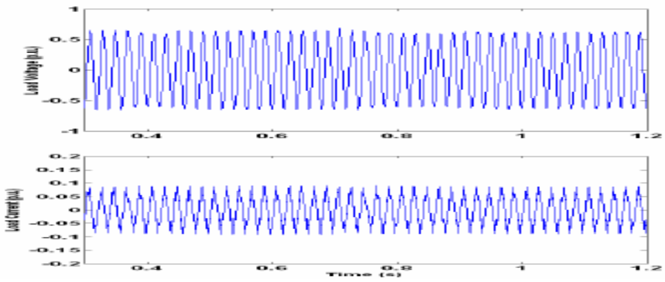

Fig. 10 Sensitive load terminal voltage and current

V. 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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