Enhancement of Voltage Quality in Isolated Power Systems

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***Abstract*— voltage sags are one of the most important power quality problems challenging the utility industry voltage sags can be compensated for by voltage and power injection in to the distribution system The use of series compensators (SCs) in improving voltage quality of isolated power systems is considered. The roles of the compensators are to mitigate the The use of series compensators (SCs) in improving voltage quality of isolated power systems is considered. The roles of the compensators are to mitigate the effects of momentary voltage sags or swells, and to control the level of harmonic distortions in the networks. A control strategy for the SC is developed to regulate power flow. This is achieved through phase adjustment of load terminal voltage. It leads to an increase in the ride through capability of loads to the voltage sags/swells. Validity of the technique is illustrated through simulation.**

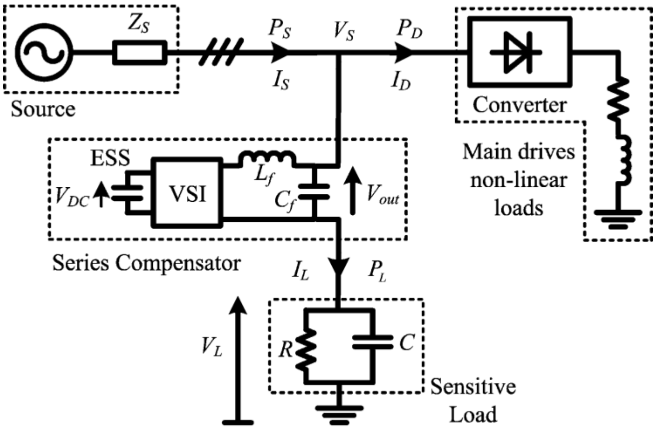
***Index Terms*—Voltage sag, Harmonic power flow, isolated power system, phase shift, series compensation, voltage restoration**

I. Introduction

ISOLATED power systems are commonly found in rural and remote areas of the world. These systems represent the alternative to grid connection, where interconnection to a large grid is not viable due to high cost and/or geographical obstacles. Furthermore, power systems such as those on board of ships, in oil exploration areas and remote mining districts are characterized by limited generating capacity, supplying loads which can consist of significant amount of motor drives and power converters. The power systems are often considered weak in that he possess relatively low short-circuit ratio, in comparison to a grid. Network voltage control becomes a challenging task as a result. The power-quality (PQ) problem is compounded as the drive-converter loads are likely to fluctuate in conjunction with the mining or exploration activities. Fig. 1 shows a typical isolated power system supplying a converter load. The RL load may be used to represent an aggregate of dc motor drives, supplied via the converter. The converter is often a controlled six-pulse rectifier through which the motor torque is regulated by adjusting the firing of the rectifier. The motor-drive load is nonlinear and would involve commutation process within the converter. The consequence would be distortions in the voltage/current waveforms in the supply system, the extents of which are likely to fluctuate as the load changes [1], [2]. In addition to the drive load, one can also expect the presence of lower power capacity-sensitive loads, such as computers or electronic controllers in the power system. The equipment Is needed to ensure the proper functioning of the exploration/mining activities. 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. s.

Fig. 1. Typical isolated power system installed with an SC.

In the latter case, voltage flickers can occur and
they can be of major concern. Thus one important consider at ion 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 PQ is 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

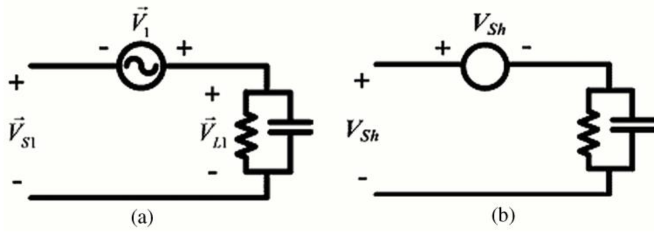
Present there. However, as noted earlier, harmonic distortions are only part of the problem faced in such a network: the variations in the drive load would result n voltage sag/swell or flickers appearing the upstream voltage V_S Thus, the challenge is to regulate the sensitive load terminal voltage 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 investigations 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.

II. HARMONIC MITIGATION AND POWER FLOW

With regard to the problem in hand, it is assumed that the Non linear converter and the sensitive loads are balanced. In what follows, symbols with the subscript “ V_P ” denote quantities which are associated with the upstream source, “ V_S ” for those associated with the sensitive load,“”with the downstream main converter drive and “ ” with the series compensator. Subscript “ I_L ”denotes the th harmonic component and “1” that of the fundamental .Voltage and current pharos are denoted with a symbol“V_L ” on the top of the respective quantities. Their magnitudes (rms) are shown as capital letters while their peak values are denoted with “ ” on top. Vectors are denoted by bold letters. As shown in Fig. 1, the central part of the SC is the voltage source inverter (VSI) and the energy storage system (ESS). As PWM switching scheme is often used in the VSI, harmonics are generated and filtering is required. and are the filter inductance and capacitance. While the detailed function of the SC under voltage sag/swell can be found in [7], [8], suffice to state that the VSI synthesizes the required voltage quantity which would be injected in series with . 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 ESS so that can be controlled.

A. Control of Harmonic Distortions

Distorted phase voltage on the upstream source-side of the sensitive load can be expressed as shown in (1) at the bottom of the page for phases a, b, and c where is the fundamental frequency, is the harmonic order; is the zero



(a) (b)

Fig. 2. Equivalent circuits of the sensitive load-SC branch for (a) fundamental component and (b) h th harmonic component

phase sequence voltage component; and are the peak and phase of the positive phase sequence voltage component;

$$V_S = \left\|\begin{matrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{matrix}\right\| = \left\|\sum_{n=1}^{\infty}[V_{on} + V_{1n}\sin(nw_o t + \Psi_{1n}) + V_{2n}\sin(nw_o t + \Psi_{2n})]\right\|$$

$$= \left\|\sum_{n=1}^{\infty}\begin{matrix} V_{on} + V_{1n}\sin(nw_o t + \Psi_{1n} = 2n\Pi/3) \\ + V_{2n}\sin(nw_o t + \Psi_{2n} + 2n\Pi/3 \end{matrix}\right\|$$

$$\left\|\sum_{n=1}^{\infty}\begin{matrix} V_{on} + V_{1n}\sin(nw_o t + \Psi_{n} + 2n\Pi/3) \\ + V_{2n}\sin(nw_o t + \Psi_{2n} - 2n\Pi/3) \end{matrix}\right\|$$

are the peak and phase of the negative phase sequence voltage component. When expressed in this manner, would be completely general and would include unbalances in the network. Clearly, distorted voltage is undesirable at the sensitive load terminals.

The fundamental components of the voltages contained in (1) are

$$VL1 = \begin{bmatrix} Vsa1 \\ Vsb1 \\ Vsc1 \end{bmatrix} = \begin{bmatrix} V11\sin(wot + \Psi 11) \\ V11\sin(wot + \Psi 11 - 2\Pi/3) \\ V11\sin(wot + \Psi 11 + 2\Pi/3) \end{bmatrix} \quad (2)$$

From (1) and (2), therefore

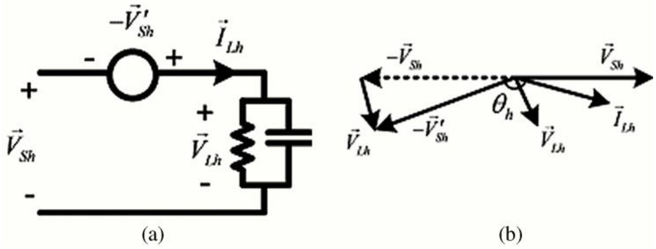
$$V_s = V_{s1} + V_{sh}$$

where contains all the harmonic components in (1). The proposed voltage injection method shown in [6] is to inject voltage components in series with and the desirable injected voltages would contain all the harmonic components in(1). Hence, from (1) and (2), the injected voltage from the SC would be Thus far, one has only considered the condition that contains harmonic distortions. However, a voltage sag/swell may appear in and hence, could differ from specified desirable value. Assume the desirable load side fundamental voltage components are Ideally, the injected voltage from the SC would be

$$V_{out} = -V_{sh} = V_{s1} - V_s$$

then have to be Extracting the fundamental component of and denoting it by the phasor , one obtains In this way, the equivalent circuit describing the sensitive load branch can then be decomposed into the fundamental frequency component and harmonic component circuits, as shown in Fig. 2(a) and (b), respectively.

$$Vs1 = \left\|\begin{matrix} V_{La1} \\ V_{Lb1} \\ V_{Lc1} \end{matrix}\right\| = \left\|\begin{matrix} V_{L1}\sin(w_o t + \Psi_{11}) \\ V_{L1}\sin(w_o t + \Psi_{11} - 2\Pi/3) \\ V_{L1}\sin(w_o t + \Psi_{11} + 2\Pi/3) \end{matrix}\right\|$$



(a) (b)

Fig. 3. Sensitive load-SC branch. (a) Equivalent circuit describing harmonic compensation in practice and (b) phasor diagram for the h th harmonic order

Under such an ideal compensation situation, there will be no harmonic component in the sensitive load current and thus, no harmonic energy exchange can exist between the SC and the external system. Energy exchange is only due to the fundamental frequency components of and .In practice, however, the SC has a finite bandwidth .A phase lag inevitably exists between and the actual injected voltage from the SC. The lag results in voltage pulses

$$V_{out} = V_{L1} - V_s = V_{L1} - V_{s1} - V_{sh}$$

appearing at the terminals of the sensitive load. As the RC sensitive load impedance decreases with frequency, the voltage pulses will cause large harmonic current distortions to appear in A practical method to limit the THD in to a pre specified level has been proposed in [6]. It involves a new strategy to control and the use of a series filter. Essentially, is

obtained from , through a lead-lag feedback scheme while the series filter reduces high-frequency harmonics in . Hence,there will be harmonic current in the circuit, as shown inFig. 3(a). As contains harmonic components, harmonic power flow can exist between the SC and theexternal system.

$$\overrightarrow{V_1} = \overrightarrow{V_{L1}} - \overrightarrow{V_{s1}}$$

B. Power Flow Control Through SC

Having described the harmonic mitigation principle andnoting that harmonic power flow would exist in the SC circuit, detailed analysis will be carried out next. For the convenience of analysis and assuming negligible unbalances in the network, a single-phase equivalent system (phase "a") is used to describe the three-phase system shown in Fig. 1. Let the fundamentalfrequency component of the sensitive load current, , betaken as the reference phasor.

In general, the instantaneous SC output power is given by (8)

$$Pc\ (t) = V_{out}\ (t)\ I_L\ (t)$$

Suppose the upstream load change has resulted in momentary sags/swells in . The aim of the compensation is to ensure the magnitude of is maintained constant. If one were to introduce phase-shift into , one would obtain a new injection voltage from that described by (6), i.e.,

where is harmonic order, and are the peak value and phase of the harmonic component of the actual injection voltage; and are the peak value and phase of the th harmonic component in .

$$Pc(t)=Vout(t)IL(t)$$

$$[VL1sain(wot+\Psi 11+\alpha)-V11\sin(wot+\Psi 11)$$

$$-\sum_{h=2}^{\infty} Vsh\sin(hwot+\Psi h)][IL\sin(wot)+\sum ILh\sinh(wot+\sigma h)]$$

where corresponds to the power flow of the fundamental frequency component. It is controllable through the introduced phase shift in . Thus, can be varied through via adjustments in . corresponds to the power flow of the harmonic components.

$$Pc=Pc1+Pch$$

$$Pc1 = 1/2V_{L1}I_{L1}\cos(\Psi_{11}+\alpha) - 1/2V_{11}I_{L1}\cos(\Psi_{11})$$

$$Pch = 1/2\sum V_{sh}I_{Lh}\cos(\theta_h) where \theta_h = \Psi_h - \sigma_h$$

In the process of varying is assumed constant over the time interval when is being adjusted. This is a reasonable assumption because the adjustmentsin can be accomplished in a much shorter time, as the rate by which the electro-mechanical drive load and therefore the harmonic level can vary is slow in comparison.

Also, as the only significant source of energy storage in the SC is the ESS, would indicate an export of power from the SC to the external system. It will cause a decrease in the voltage across the ESS. Conversely will beginto rise if the SC starts to import from the external system.Variations of will affect the compensation capability of theSC and excessive voltage rise will damage the ESS. Hence,has to be controlled within acceptable range, that is, has to

$$vsh = Vm[0.18\sin(5wot-140^0)+0.24\sin(7wot-30^0)$$

$$+0.08\sin(11wot-148^0)+.........]$$

$$iDh(t)$$

$$=3.46\times\frac{Id}{\Pi}[1/5\sin(5wot+30^0)+1/7\sin(7wot-30\ )$$

$$+\frac{1}{11}\sin(11wot-30^0)+....]$$

be regulated. Fig. 3(b) shows the phasor diagram of the harmonic order compensation by the SC. For perfect harmonic voltage cancellation,the ideal voltage injected by the SC is but due to the SC bandwidth limitation described earlier, the actual voltage injected is . Although the phase difference between and would depend on the SC controller design, this phase difference is expected to be small in practice if the cancellation is to be reasonably effective.

Since the sensitive load is assumed to be resistive-capacitive, the th harmonic voltagecomponent across the load lags the harmonic current. The phase angle between and is therefore larger than 90 , as shown. Thus the harmonic power, that is, the SC will import real power from the external system. The extent of the power import will depend on the injection voltage, which, in turn, depends on the main drive load operating conditions. This aspect will be examined in greater details next.

C. Harmonic Power Flow

In Fig. 4, the main load is shown as a dc drive system. The dc motor, represented by the equivalent RL circuit, is assumed to be fed by a six-pulse controlled converter. The firing angle of the converter determines the average value of the output voltage. The converter output current can be controlled via a PI regulator which changes . In this way, the effect of a load change can be readily studied by altering the reference current. Details of the control technique can be found in [9].The main converter load is the dominant harmonic source in the power system due to its much larger capacity, compared to the SC and sensitive load. The SC is assumed to be "ideal" in that whatever harmonics generated by the VSI are effectively

$$P_{D1} = V_d I_d = 1.53V_m I_d$$

dealt with by its LC filter. The SC is a harmonic "sink." In this way, the harmonic power produced by the nonlinear main drive load is dissipated in the upstream source impedance and is absorbed by the sensitive load. The harmonic power flow to the up stream source and into the sensitive load are as shown in Fig. 4.

$$P_{Dh} = -0.02P.U$$

To assess the value of , the harmonic contents of and have to be known. In order to do so, the following assumptions are made: the upstream source consists of balanced sinusoidal EMF of constant voltage with equal inductances; its phase "a" terminal voltage is of the form and is assumed to be ripple free.

$$PSh = -\frac{0.0014m}{q^{2}} P.U$$

The firing angle changes as load condition varies and in general, and the overlap angle of the converter determine the exact waveform of [10]. Harmonic components of

$$P_{Lh} = \frac{(THDv)^{2}}{k} = \frac{0.001}{k} P.U$$

and could be obtained through Fourier analysis and can be evaluated. Furthermore, once has been determined, can also be determined as the source impedance is assumed known. The balance of the harmonic power is diverted

$$P_{Ch} = P_{sh} = P_{Dh} - P_{lh}$$

$$= (0.02 - \frac{0.0014m}{q^{2}} - \frac{0.001}{k})$$

to the SC branch. Part of this harmonic power will be absorbed by the sensitive load. Once , and have been obtained, the harmonic power imported by the SC ,could be evaluated. Numerical examples will now be used to illustrate how the harmonic power flow in the network can be assessed.

Example 1: Suppose the ratio between the VA capacity of the main drive load and that of the sensitive load is . The upstream source fault level is “ ” times that of the main drive load capacity. The ratio of at the fundamental frequency is , that is, .Assume the drive-load converter operates at and an overlap angle . The resulting waveforms of and can be derived using the expressions given in [10]. Fourier analysis of and yields the following characteristic harmonic components

From (12) and (13), the harmonic power (up to the 11th harmonic) generated by the main drive load can be obtained

The average dc voltage can be calculated using the results shown in [10]

and, therefore, the power of the fundamental frequency component of the main drive load is

The converter is assumed lossless. Using and as base values, the harmonic power exported by the main load is

As the system short-circuit ratio is and can be calculated. Apply and from[11], it can be readily shown that

Next, suppose the THD of the voltage at the terminals of the sensitive load is to be limited to (say) 3%. Thus, can be obtained using the result shown in [12]

Hence, the harmonic power imported by the SC is estimated to be As an illustration, for typical values of and, the last expression shows that p.u. Since it is assumed that the sensitive load capacity is that of the main drive load, here fore corresponds to some 19% of the sensitive load capacity.

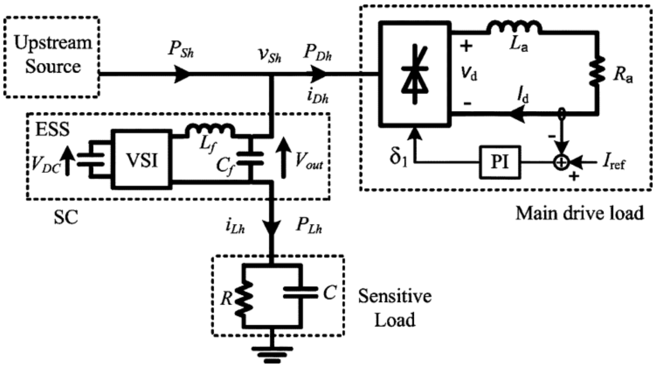


Fig. 4. Harmonic power flow in the isolated system h th harmonic component

$$vsh = Vm[0.18\sin(5wot - 140^{0}) + 0.24\sin(7wot - 30^{0}) + 0.08\sin(11wot - 148^{0}) + ...]$$

$$iDh(t) = 3.46 \times \frac{Id}{\Pi}[1/5\sin(5wot + 30^{0}) + 1/7\sin(7wot - 30\ \ ) + \frac{1}{11}\sin(11wot - 30^{0}) + ...]$$

In this case, is seen to be equivalent to some 67% of the sensitive load capacity, if the same numerical values of and used earlier were again assumed. This is a substantial amount of absorbed power, in so far as the sensitive load is concerned. The above examples serve to illustrate that the operating states of the converter will affect the harmonic power exported by the main load which, in turn, determines the amount of the harmonic power absorpted by the SC. The dominant factor governing appears to be , that is, a significant part of will be absorpted by the SC. For a conceivable range of the converter operating conditions, it is possible to obtain expressions for , as illustrated earlier.

III. VOLTAGE RESTORATION

Having considered harmonic power flow in the isolated power system, voltage restoration will be examined next. As stated earlier, voltage control of the ESS is necessary to ensure the proper operation of the SC and to protect the device. Thus it is desirable to regulate the power transfer between the SC and the external system so that across the ESS of the SC can be maintained .Once this is achieved, the SC will be able to exercise network voltage control, in a manner described in [7] and [8]. The SC will assume this role of voltage control until such time when the excitation system of the upstream generator becomes effective in forcing the generator to share the voltage regulation duty. However ,if the excitation system is a slow-acting electromechanical type, the sensitive load would have to rely very much on the SC to achieve a constant . It is therefore necessary to examine the extent by which the SC can exercise such control .Further more, in terms of voltage quality, it is the fundamental component of which is of the greatest importance. Hence in what follows, the focus is on maintaining the magnitude of this voltage component, denoted as in Fig. 5.

The condition of zero power transfer between the SC and the external system is examined first. From (11), this means that , that is, when

$$P_{C1} = -P_{Ch}$$

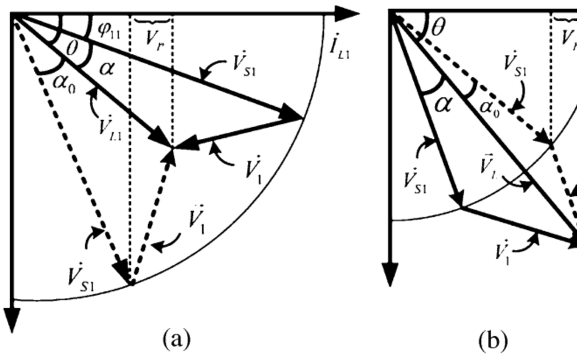


Fig. 5. Phasor diagram showing voltage restoration during (a) voltage swell and (b) voltage sag: fundamental frequency component

$$P_C = P_{C1} + P_{Ch} = 0$$

As shown in Section II, it is concluded that the SC absorbs harmonic power from the external system, that is, . Thus, from (24), at zero power transfer, the SC should export power of the fundamental frequency component equal to an amount in order to balance the imported harmonic power. Next, define an equivalent fundamental frequency component voltage of the SC injected voltage such that The last expression means that when the projection of the fundamental frequency component of (shown as in Fig. 5) onto is , the condition for zero power transfer is reached. As shown in the previous Section, and are known quantities for a given power system operating condition. Hence from(25), can be obtained readily.

A. Voltage Swell

When the drive load varies and causes a voltage swell, > , as shown in Fig. 5(a), where is shown as the reference phasor. Since denotes the desired voltage magnitude at the sensitive load terminals, the aim is to maintain it constant through the action of the SC. Assume the sensitive load is of constant power factor at the fundamental frequency. There fore from (11), , that is, the phase angle between and is constant at . is the phase shift described in Section II. From (7), the SC injected voltage is and since can be rewritten as

The situation depicting and by the solid lines inFig. 5(a) shows that is negative. This corresponds to the situation when the SC imports from the external system. By Continuously adjusting and shifting in the clockwise direction, will become less and less negative and it eventually will become positive, that is, the SC will then export to the external system. The condition shown by the dotted linesin Fig. 5(a) is when the projection of onto is equal to the value of given by (25) precisely. Hence, at this point,theSCoutput power contributed by the fundamental frequency component voltage and current is Again from(25),andthuszeropowertransferconditionbetweentheSCandtheexternalsystemisreached.Mathematically,this can be expressed by the condition when

For a voltage swell, is negative, that is, lags at zero power transfer. At this instance, the phase angle of is .Furthermore, one concludes that the SC will import power when , that is, is shifted in the counterclockwise direction from the condition .Conversely, if were adjusted in the clockwise direction, and as the projected component of onto is larger than ,then . The SC would then export power to the external system.

The above analysis suggests a method to regulate the ESS voltage. If decreases below a set value, it means that the SC is exporting total power to the external system. Onean then reverse the fall in by adjusting the VSI firing angle to effect a counter-clockwise phase shift in such that, in order to force a net import of and vice-verse. In this way, can be regulated through the control of . Since the power factor angle , the factors and (as defined by (29))can be readily determined online, the calculation for can beaccomplished as part of the SC real-time control system. Thephase-shift control strategy to regulate can be realized.It is interesting to note that from (25), if increases due to drive load changes, and will also increase. This means that also increases. Hence, the SC voltage rating has to be adequate in order to cater for this injection method.

B. Voltage Sag

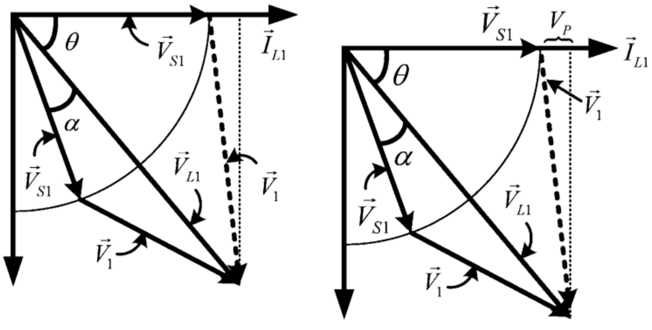
The above analysis can be extended to deal with the event of voltage sag, that is, . Fig. 5(b) shows a general phasor Diagram during voltage sag. By similar reasoning as shown for voltage swell, when transfer when . This is shown by and in dotted lines in the figure. From this condition of zero power transfer,if one were to adjust to shift it in the counter-clockwise direction, when leads by an angle where . The SC then imports power from the external system. Conversely, adjusting in the clockwise direction can leadto . When this occurs, , the SC will export real power to the external system. An example of such a condition is shown by and by the solid lines shown in Fig. 5(b).Hence if it is noted that is above a set value, it will then be necessary to introduce a phase shift in such that. The SC then exports realpowertothexternalsystem.TheESSvoltageshoulddecrease. Conversely,if is below the set value, phase should be adjusted to meet the condition If one were to exclude harmonic power from the above analysis, such as in [7], [8], [13], Fig. 6(a) shows the condition in which the severity of the sag is such that .It can be seen that by shifting until it aligns with is exported from the ESS to the external system at the minimum value. This is the condition indicated by assuming the position of the dotted line in the figure. The minimum exported power i

In the event if is already lower than its desirable set value, one would need to adjust in such a way that can be absorbed from the external system. From the phasor diagram, however ,it shows that it is impossible to effect such a condition for power absorption. At best, with adjusted to be in-phase with the SC exports at the minimum value given by (31). It can only minimize the rate of the decrease of .With the harmonic power flow included in the compensation process, the situation improves somewhat. Fig. 6(b) shows the most severe sag that can be compensated for when is shifted to be in phase with , and the harmonic power absorbed by the SC is given by (25), that is, ,with being equal to that shown in the figure. In this way, zero power exchange between the SC and the external system has been achieved. From Fig. 6(b), it is seen that

Hence, the most severe voltage sag that the SC can compensate for while maintaining zero power transfer is where, as defined by (29), . Hence, by adjusting and taking advantage of the presence of the harmonic power , the proposed compensation strategy compares favorably with that shown in Fig. 6(a) where the most severe sag that can be compensated for is , if is to be maintained constant. The proposed method improves the ride through capability of the sensitive load by a margin , through the SC absorbing the harmonic power generated by the main load and converting it into real power for supporting the sensitive load voltage. From (33), clearly the most onerous ride through condition is when the sensitive load power factor is unity. Also, the following observation can also be arrived at.

1) Since decreases with . However, from(25), it is seen that decreases with an increase in for a given . Hence, the margin would be at the minimum when is at its maximum value (i.e., when the sensitive load is at full load).

2) depends most significantly on which in terms bears a complex relationship to the operating state of the motor drive. While it is difficult to generalize this relationship, it is clear that when the motor load is at full load ,full-conduction in the rectifier occurs and harmonic distortions are expected to be at the minimum. Hence , correspondingly, will be at the minimum. Again from



(a) (b)

Fig. 6. Phasor diagram of voltage sag condition when V =V = <cos (a) without harmonic power taken into consideration and (b) with harmonic power taken into consideration

1) 25), and, therefore, will be at the minimum.

Based on the above observation, it can therefore be concluded that one most onerous sensitive load ride through condition would be when the load is at full load, unity power factor, while is at the minimum or when the motor load is operating at rated power.

Also from (33), one notices that the most severe voltage-sag that the SC can provide load ride through is when . For small is approximately equal to the load power factor.

From Fig. 6(b), the maximum injection voltage is approximately equal to sin . Hence, the SC must be rated to be at least sin times that of the sensitive load.

Although not shown in the above analysis, similar conclusions can also be reached if the power factor of the sensitive load is lagging.

IV. ILLUSTRATIVE EXAMPLES

The example shown on Fig. 4 may now be used to verify the effectiveness of the SC in enhancing the voltage quality of the power system. The upstream generator is represented as a220-V voltage source, with its AVR action ignored. The source impedance is assumed to be 0.05 p.u. and . The main load converter is assumed to be a six-pulse controlled rectifier. The dc motor, as shown in Fig. 4, has and mH. The rating of the dc load is 2 kW and it is also the base value chosen for the system. The current of the motor is controlled and load change is simulated by changing the of the motor. The capacity of the sensitive load is assumed to be0.2 kVA (i.e.,) and its power factor at the fundamental frequency is 0.75 leading. The sensitive load level is assumed to be at full load in these examples. The SC was modeled as a PWM inverter and its detail model is given in [13]. A capacitor is used as the ESS. The simulations were accomplished using MATLAB

The voltage at the sensitive load terminals is as shown in Fig. 7 when a load change occurs but without the SC in service. Before the load change, the motor drive is at 0.5-p.u. loading and it can be shown that has a THD level of 30%

Fig. 8 shows the corresponding waveforms when the SC is in service. With harmonics compensation by the SC, the sensitive load is protected against the harmonic distortion and the THD of the voltage has been significantly reduced to 3%.

The harmonic power flow (expressed on the base of the sensitive load capacity of 0.2 kVA) in the isolated power system is shown in Fig. 9. Prior to a % load change, imported by the SC during compensation is about 0.13 p.u. On a 0.2-kVA base, p.u. and from (25), p.u. Thus, p.u. According to (33), the sag ride through limit

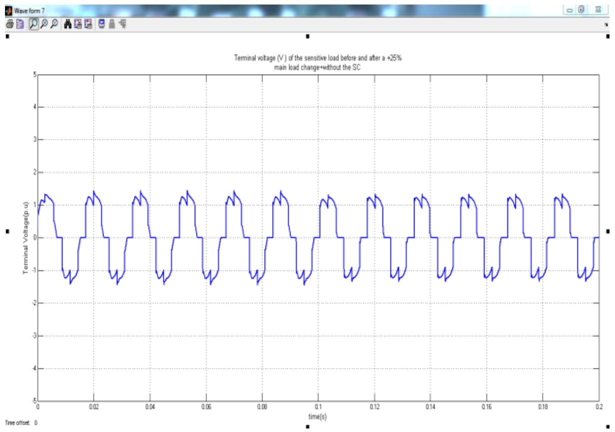


Fig. 7. Terminal voltage (V) of the sensitive load before and after a +25%main load change—without the SC.

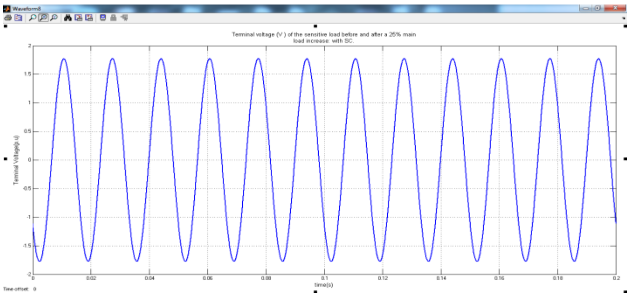
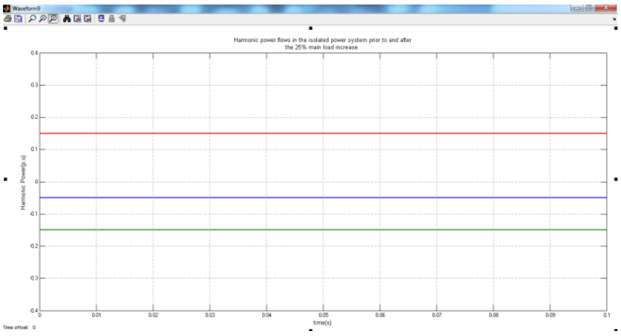


Fig. 8. Terminal voltage (V) of the sensitive load before and after a 25% mainload increase: with SC.



. Fig. 9. Harmonic power flows in the isolated power system prior to and after the 25% main load increase.

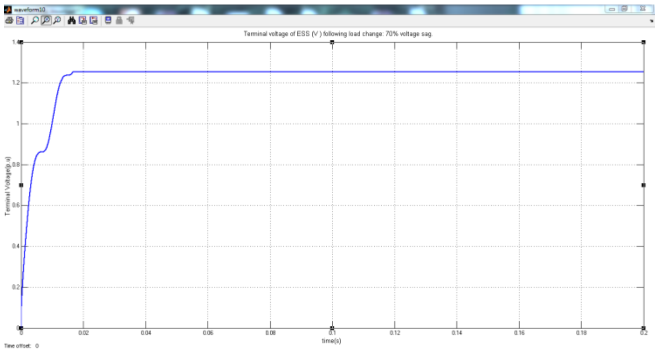


Fig. 10. Terminal voltage of ESS (V) following load change: 70% voltage sag.

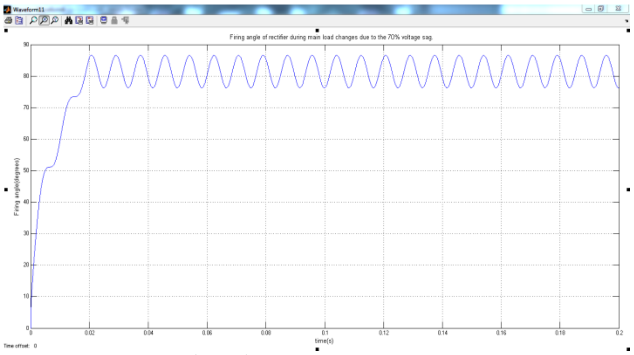


Fig. 11. Firing angle of rectifier during main load changes due to the 70% voltage sag.

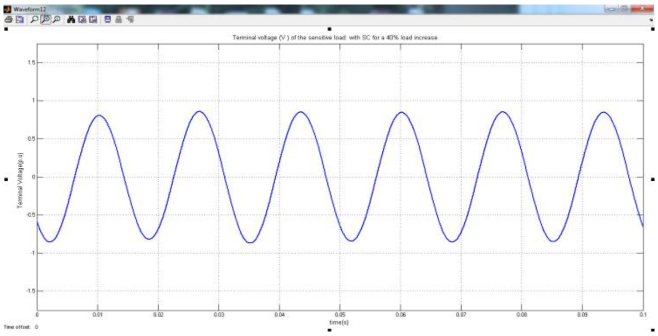


Fig. 12. Terminal voltage (V) of the sensitive load: with SC for a 40% load increase.

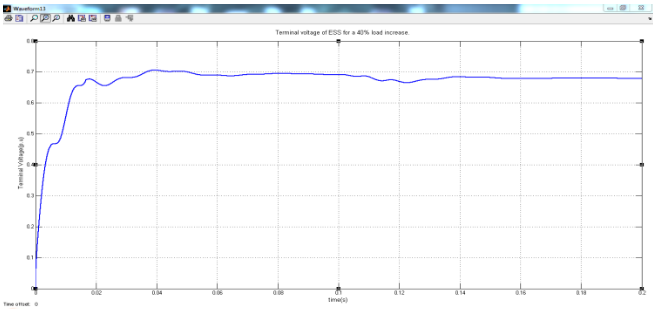


Fig. 13. Terminal voltage of ESS for a 40% load increase.

is about 0.62 p.u. The % load change has resulted in a 70% voltage sag, as shown in Fig. 7, when the SC is not in service. The load change has caused to decrease to about 0.1 p.u., which means that also decreases correspondingly. is now about 0.65 p.u. but it is still less than the load power factor. Hence the SC can still assist the load in riding through the sag ,as shown in Fig. 8. Fig. 10 shows the ESS voltage during the voltage restoration: decreases marginally and is restored in some 10 cycles or so in the face of the voltage sag. Fig. 9 shows that as the load changes, also varies because the firing angle is adjusted. This can be seen in Fig. 11.

From the above results, the VA capacity of the SC has been evaluated using Fig. 5(b) and is estimated to be some 36% of the sensitive load rated capacity. The corresponding . fig. 12 shows the waveform of during a 50% voltage sag when the dc motor load is increased by 40%. The sensitive load is seen restored through the voltage sag. However, the load increase is so large that it has resulted in to be below the limit predicted by(33).is sustained only through the continuous export of from the ESS. Hence, the voltage of the ESS cannot be maintained, as is shown in Fig. 13.Clearly this is not a sustainable operation as the ESS energy will eventually be depleted and the SC will no longer be effective.

Similar studies have also been carried out under voltage swell conditions to confirm that the SC can indeed provide satisfactory y ride through performance for the power system. A full prototype of the SC is under development, with the view to use it to validate the results of the analysis described earlier.

V. CONCLUSION

. The power system contains significant proportion of fluctuating nonlinear load and a high level of harmonic distortions is observed. Voltage quality improvement in an isolated power system through series compensation has been investigated A method to control the injection voltage of the SC so that it can mitigate the effects of the harmonics has been proposed.The SC is also designed to maintain the fundamental frequency component of the terminal voltage of protected sensitive load. In the process of harmonic voltage compensation, it is shown that power exchange exists between the SC and the external network.Based on the analysis of the harmonic real power flow in the power system, it is seen that the SC would import harmonic real power from the external system. A new SC control strategy is then proposed which involves the phase adjustment of the fundamental frequency component of the sensitive load terminal voltage.. The capacity of the SC required is mode stand, therefore, makes it a viable device for such an application.Simulations have confirmed the effectiveness of the proposedmethod, as it is applied on the SC to achieve improved quality of supply in the power system. Through the analysis on the power exchange, it is shown that the load ride through capability during voltage sag can be improved with the support of the harmonic real power absorbed by the SC

REFERENCES

[1] I. Jonasson and L. Soder, "Power quality on ships-a questionnaire evaluationconcerning island power system," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Jul. 2001, vol. 15–19, pp. 216–221.

[2] J. J. Graham, C. L. Halsall, and I. S. McKay, "Isolated power systems: Problems of waveform distortion due to thyristor converter loading," in *Proc. 4th Int. Conf. Power Electronics and Variable-Speed Drives*, Jul. 1990, vol. 17–19, pp. 327–330.

[3] *ITI (CBEMA) Curve Application Note*, [Online]. Available: http://www.itic.org., Inf. Technol. Ind. Council (ITI).

[4] J. C. Das, "Passive filter—Potentialities and limitations," *IEEE Trans. Ind. Appl.*, vol. 40, no. 1, pp. 232–241, Jan. 2004.

[5] H. Akagi, "New trends in active filter for power conditioning," *IEEE Trans. Ind. Appl.*, vol. 32, no. 6, pp. 1312–1322, Nov. 1996.

[6] S. S. Choi, T. X.Wang, and E. K. Sng, "Power quality enhancement in an isolated power system through series compensator," presented at the 15th Power System Computation Conf., Liege, Belgium, Aug. 2005.

[7] N. H. Woodley, L. Morgan, and A. Sundaram, "Experience with an inverter-based dynamic voltage restorer," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1181–1186, Jul. 1999.

[8] S. S. Choi, B. H. Li, and D. M. Vilathgamuwa, "Dynamic voltage restoration with minimum energy injection," *IEEE Trans. Power Syst.*, vol. 15, no. 1, pp. 51–57, Feb. 2000.

[9] P. C. Sen, *Principles of Electric Machines and Power Electronics*, 2nd ed. New York: Wiley, 1997.

[10] E. W. Kimbark, *Direct Current Transmission*. New York: Wiley, 1971.

[11] J. P. Tamby and V. I. John, "Q'HARM-a harmonic power-flow program for small power systems," *IEEE Trans. Power Syst.*, vol. 3, no. 3, pp. 949–955, Aug. 1988.

[12] G. J. Wakileh, *Power System Harmonics: Fundamental, Analysis and Filter Design*. New York: Springer, 2001.

[13] E. K. K. Sng, S. S. Choi, and D. M. Vilathgamuwa, "Analysis of series compensation and dc link voltage controls of a transformerless selfcharging dynamic voltage restorer," *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1511–1518, Jul. 2004.