CUSTOM POWER DEVICES FOR VOLTAGE SAGS MITIGATION: A TECHNO-ECONOMIC ANALYSIS

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Abstract: *The increased concern about the financial losses due to voltage sags and interruptions plus the advancements in power electronics technology have led to the innovation of very fast acting intervening equipment that can mitigate such disturbances at the facility entrance. Although significant improvements in the overall power quality can be achieved, however, the high cost of these custom power devices can offset the benefits resulting from their application. The problem therefore, is one of finding a compromised solution that makes technical and financial sense. In this paper, the technical merits of the custom power devices are highlighted, along with their effectiveness in mitigating sags and/or interruptions. The costs of each application are financially analyzed together with a procedure for the decision maker to compare the payback or the revenue of investment in such devices. A case study of an oil refinery in Alexandria, Egypt is considered to validate the proposed procedure. The results showed that the best solution would be the use of a Static Transfer Switch (STS) provided with two feeders electrically separated. Otherwise, the Dynamic Voltage Restorer (DVR) will be the best solution.*

Keywords: *Voltage Sags, Short Interruptions, Power Quality, Custom Power Devices, Techno-economic Analysis*

1. Introduction

Voltage sags and short interruptions can be generally described as brief voltage reduction events, followed by restoration of the normal supply conditions. Voltage sags and short interruptions are probably the most serious power quality problems, as they are frequent causes of malfunctioning electrical equipment in industrial installations, leading to costly process shutdowns [1].

Custom power devices are a special category of power conditioning equipment, used to protect the entire facility from such voltage disturbances. Custom power devices have to work within parts of a cycle, thanks to the advancements in power electronics technology, such that the load bus will not be affected by the supply disturbance [2].

The study work in this paper tries to answer two questions; which custom power device to use and at what cost. The paper proposes a methodology for the decision makers, to compare the technical merits and limitations of these devices, along with an economical evaluation of their costs against the financial losses associated with sags and interruptions.

2. Voltage sags and short interruptions

2.1 Definitions

The IEEE Std. 1159-2009 defines voltage sag as: A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min. The amplitude of voltage sag is the value of the remaining voltage during the sag. The IEEE defines a momentary interruption as: A complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s. A temporary interruption is: The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 3 seconds and 1 minute [3].

The IEC terminology for voltage sag is ***dip***. The IEC defines voltage dip as: A sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period of time, from half a cycle to a few seconds. The amplitude of a voltage dip is defined as the difference between the voltage during the voltage dip and the nominal voltage of the system expressed as a percentage of the nominal voltage. The IEC defines a short supply interruption as: The disappearance of the supply voltage for a period of time not exceeding 1 min. Short supply interruptions can be considered as voltage dips with 100% amplitude [4].
Fig. 1 shows an rms representation of voltage sag, the sag starts when the voltage decreases to lower than the threshold voltage Vthr (0.9 pu) at time T1. The sag continues till T2 at which the voltage recovers to a value over the threshold value, hence the duration of the voltage sag is (T2-T1) and the magnitude of the voltage sag is sag to Vsag [5].

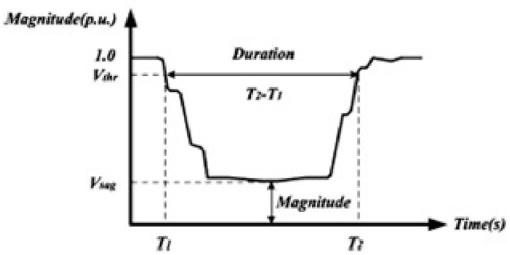

Figure 1. Voltage sag

2.2 Causes

Reports of voltage sags relate voltage sags to lightning, animal contact, fallen tree limbs, storms and accidents, in addition to unavoidable faults and switching operations on the transmission and distribution networks. Energizing of heavy loads, starting of large motors and transformer saturation can also cause voltage sags, although of shallower values [6-7].

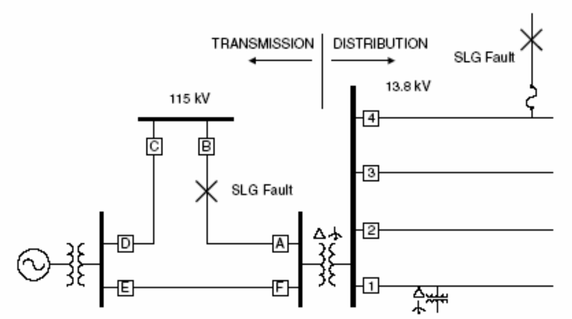

Figure 2. Fault locations on the utility power system

Consider the transmission and distribution system shown in Fig. 2. When a fault occurs at the distribution feeder (4), the feeder breaker will operate (open), leading to a complete interruption on this feeder. The users on the faulted circuit on the load side of the operating protective device will see a permanent or temporary interruption according to the type of fault and the protective scheme. During fault, the transmission circuit as well as the other feeders will contribute to feed the fault. As a result, all loads on the other three circuits will suffer a temporary voltage sag, which lasts as long as the circuit breaker on the parallel feeder opens and interrupts the flow of the fault current. Due to the impedance of the step-down transformer, most distribution faults will affect only the users who share the distribution bus. A much more common event would be a fault somewhere on the transmission system. Note that to clear the fault shown on the transmission system of Fig. 2, both breakers on the two sides of the fault must operate. In such case, only one of the two lines supplying the distribution substation has a fault. Therefore, customers supplied from the substation should expect to see only a sag, not an interruption [8].

2.3 Effects

Voltage sags and short interruptions affect the operation of equipment in various forms. Digital electronic devices, particularly those with a memory, are extremely sensitive to very short-duration power disturbances. Programmable logic controllers, adjustable speed drives, and data terminals are a few examples of sensitive loads that often fall victim to momentary voltage disturbances [9].
Industrial loads consisting of large induction motors suffer from sags and short interruptions in a different manner. As the supply voltage to the induction motor decreases, the motor speed decreases. Depending on the severity and the duration of the voltage reduction event, the motor speed may recover to its normal value as the voltage amplitude recovers. If the voltage magnitude and/or duration is lower than certain limits, the motor may stall and would be taken out of the system [10].

2.4 Mitigation

Mitigation equipment can be grouped into two classes:
i) Load-side (equipment level) solutions: Generally, the ratings of these solutions are such that they are installed directly at the sensitive loads. Examples of these devices include the Motor-Generator (MG) sets where energy is stored in flywheels to support the load during any interruption or sag. An office necessity today is

The Uninterruptible Power Supply (UPS) where batteries are used to supply power to the load. Other solutions include the Constant Voltage (ferro-resonant) Transformer (CVT), which is excited at a high point on its saturation curve, thus providing a constant output voltage regardless of the primary input voltage, and the Static Voltage Regulator (SVR) or electronic tap-changer which changes the turns ratio of a transformer to compensate for the input voltage variations. [11].

ii) ***Source side (facility level) solutions (Custom power devices)***, applied in the medium voltage distribution system of an electric utility with the purpose of protecting an entire plant, with load ratings of the range of a few MVA [12].

3. Custom power devices

The concept of custom power is the employment of power electronic or static controllers in medium voltage distribution systems for the purpose of supplying a level of power quality that is needed by customers sensitive to power quality disturbances. Custom power controllers may include static switches, inverters, converters, injection transformers, master control modules, and energy storage modules [13].

Existing Custom Power Devices include the solid state or the Static Transfer Switch (STS), working by transferring the load bus to another healthy feeder in sub-cycles, the Dynamic Voltage Restorer (DVR), working by boosting the voltage at the load bus during voltage sags, utilizing an energy storage unit and a voltage source converter, and the Backup Storage Energy Systems (BSES), working by isolating the supply once a disturbance is detected and feeding the load from an energy storage unit and an inverter.

Each equipment has its merits and limitations. For example, the STS requires the presence of another feeder that is electrically distinct from the main feeder, and cannot protect against transmission system sags of common transmission circuit. The DVR can protect for a 50% sag for a couple of seconds but cannot protect against complete interruptions. The BSES requires a huge energy storage unit (either batteries or flywheel) which requires large maintenance and operating costs.

3.1 Dynamic Voltage Restorer (DVR)

The DVR is a custom power device connected in series with the distribution feeder, sometimes called the Static Series Compensator (SSC). The DVR provides a controllable voltage, whose phasor adds to the source voltage to obtain the desired load voltage. In its simplest configuration, shown in Fig. 3, the DVR consists of the following components [14-16]:

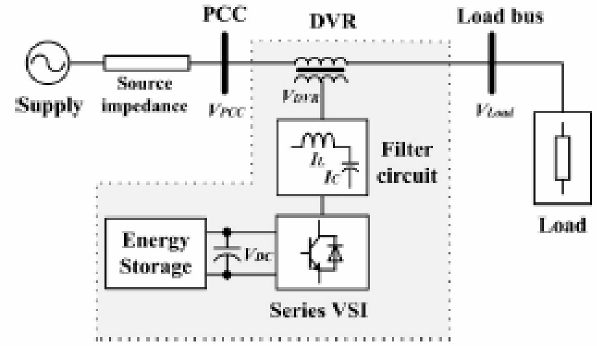

Figure 3. Dynamic Voltage Restorer (DVR)

1. ***Energy storage unit***, which is used to provide the missing energy during the sag condition. Commercially available DVRs use large capacitor banks for energy storage. The capacity of the energy storage device determines the ride-through time for the load. DVRs can be configured to use line energy supply; that is, they absorb the energy that is to be injected into the distribution circuit from the utility feeder itself.
2. ***Voltage Source Inverter (VSI), or Voltage Source Converter (VSC),*** which converts the dc voltage from the energy storage unit to a controllable ac voltage to be inserted with the line voltage. The VSI must treat each phase independently and must be capable of handling both sags and swells simultaneously. The switches of the inverter are switched independently of each other, normally according to a Pulse Width Modulation (PWM) pattern, with high switching frequency. Existing DVRs are usually sized for 50% maximum voltage injection.
3. ***Injecting transformer,*** connected in series between the source and the load, and which injects the DVR voltage at the load bus.
4. ***Filter circuit*****,** normally, a second-order LC filter is inserted between the inverter and the transformer to cancel high frequency harmonic components in the inverter output voltage.
5. ***Bypass switches and Control circuits,*** through which the DVR may be configured to operate as a standby compensator where the inverter is not actively in the circuit until triggered by a voltage sag event. Alternatively, the DVR may be working continuously during normal and abnormal conditions.

The major disadvantage of the DVR is that it does not protect a load against an interruption [17].

3.2 Static Transfer Switch (STS)

The Static Transfer Switch (STS) allows fast transfer of the loads from a primary source affected by sag or interruption to an alternative feeder. The STS consists of three main components, as shown in Fig. 4 [18]:

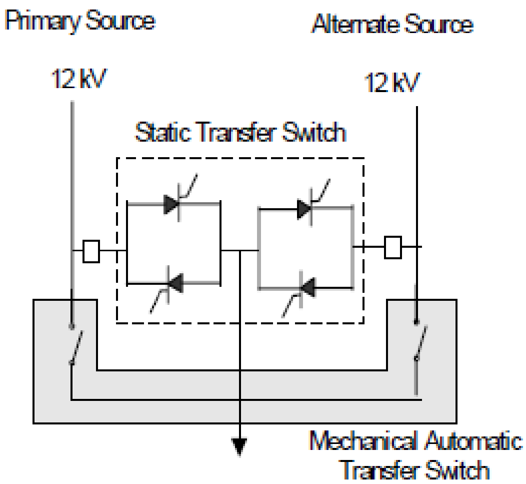

Figure 4. Static Transfer Switch (STS)

1. The static transfer switch STS, consists of two three-phase ac thyristor switches connected back to back (anti-parallel), directing power from two independent feeders to the load.
2. The mechanical bypass switch MTS, operates as a standard mechanical transfer switch when the static transfer switch is out of service.
3. Isolating switches and Control, during normal condition, the switch connected to the primary feeder is kept closed and the switch on the secondary feeder is kept opened. On the detection of a sag or an interruption on the primary feeder, the switches on the secondary feeder turn on immediately and that on the primary feeder turn off at the first natural current zero, hence transferring loads to the healthy feeder, thus providing a seamless transfer of electrical energy between the two feeders.

A requirement is that a secondary feeder, independent from the main source (e.g. a feeder to another substation), must be available. The STS cannot protect against sags originating in the transmission system, which will also affect the alternative supply [18].
The main problem with the STS comes from plants with a high percentage of motor loads, a "voltage collapse" problem may occur due to motors drawing much current to re-accelerate, and may be tripped by protection devices due to the high current drawn [19].

3.3 Backup Storage Energy System (BSES)

A backup stored energy system (BSES) disconnects a protected load from the utility supply within milliseconds of the detection of a disturbance and supplies the entire load using stored energy. Typical sources for the stored energy are batteries, flywheels, or superconducting magnetic coils. A BSES unit typically consists of a static source transfer switch (isolation switch), energy storage system, voltage source converter, and isolation transformer, as shown in Fig. 5.

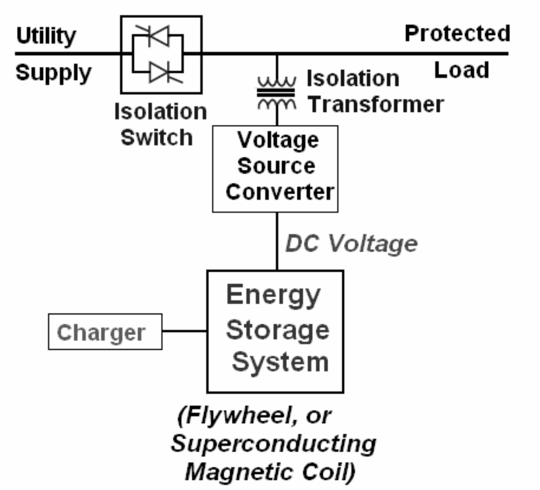

Figure 5. Backup Energy Storage System (BESS)

A BSES can be seen as an alternative to an uninterruptible power supply (UPS) when the load power increases. During normal operation, power coming from the ac supply is rectified and then inverted, and the batteries only serve to keep the dc bus voltage constant to avoid high steady-state losses. During a voltage sag or interruption, the battery block releases energy to supply the load. One of the main advantages to the BSES compared to the DVR is that it is able to carry a load through a voltage interruption. Because of this, however, its storage requirements are higher. On the other hand, since a BSES unit disconnects the protected load from the utility system, its converter must be rated to carry the entire rating of the protected load.
For storing the necessary energy, batteries or flywheels (rotary UPS) or Super Magnetic Energy Systems (SMES) can be used. The main advantages of SMES as compared to the batteries are the reduced size and lower maintenance requirements, but a cryostat and refrigeration system is also needed negating some of the size advantage. On the other hand, capacitors and battery options have many more electrical connections than the superconducting coil [20].

4. Economic evaluation

4.1 Losses due to sags and interruptions

A common misconception is that power quality issues are technical problems, but in fact, power quality is a techno-economic problem. Reference [21] estimated the average costs of disturbances as shown in Table I:

Table I
Losses due to sags and interruptions

Sector	Cost of voltage sags and interruption / event (in US $)
Semiconductor Industry	2,500,000
Credit Ccard Processing	250,000
Equipment Manufacturing	100,000
Automobile Industry	75,000
Chemical Industry	50,000
Paper Manufacturing	30,000

It should be noted that not all voltage sags lead to process shutdown. Costs will typically vary with the severity of the sag. This relationship can often be defined by a matrix of weighting factors. The weighting factors are developed using the cost of a momentary interruption as the base. Usually, a momentary interruption will cause a disruption to any load or process. Voltage sags will always have an impact that is some portion of this total shutdown. If a voltage sag to 50% causes 80% of the economic impact that an interruption causes, then the weighting factor for a 50% sag would be 0.8 [22]

Financial losses due to tripping events can be calculated according to [23]:

Losses =
Value of lost production + shutdown costs – shutdown savings

- The value of lost production is equal to the customer's expected revenue without the trip. It is the value of the product or services that would not produced for the duration the facility is shut down.
- Shutdown related costs are those costs directly incurred because of the trip. These include equipment damage costs, material damage costs (the most catastrophic forms of damage to raw materials occur in processes that require continuous electricity), backup generation costs, labor costs to restart production, and any penalties due to delay in product delivery, shipping, etc. Some firms would experience significant losses as a result of environmental fines associated with violations of clean air and water regulations if electric power failed.
- Shutdown related savings are cost savings that result from the interruption. Customers never really experience savings as a result of an electrical outage. However, these are costs unpaid or gained. Savings include costs of labor and materials that were not used during the outage, the value of fuel and electricity that was not used, and the value of any scrap that was generated as a result of the shutdown.

The above discussion assumes that all future PQ events and various costs associated with mitigation devices are exactly known. However, none of these data is known with certainty in reality, thus opening the door for probabilistic methods, which treat all inputs as random variables. The output in this case will be a probability distribution of all the possible outcomes for the input values [24].

4.2 Custom power costs

Each solution technology needs to be characterized in terms of cost and effectiveness. In broad terms, the solution cost should include [25]:

1) Fixed Costs: The fixed costs mainly consist of the mitigation device cost and the cost to install it including labor hours, footprint of the device, time and so forth.

2) Operating Costs: The operating or variable costs are those which allow the mitigation device to work. These operating costs consist of heating losses, maintenance and additional costs such as replacement of batteries at the end of their life, air conditioning to cool the battery room.

The investment costs for the used mitigation methods are given in Table II [22].

Table II
Example costs for different PQ mitigation techniques

Alternative	Cost ($)	Operation & maintenance annual costs (%)
BSES (Battery ride through)	500 $ / kVA	15 %
DVR (50% boost)	300 $ / kVA	5 %
STS (10 MVA)	600,000 $	5 %

Table II provides an example of initial costs and annual operating costs for some general technologies used to improve performance for voltage sags and interruptions. Besides the costs, the solution effectiveness of each alternative must be quantified in terms of the performance improvement that can be achieved. Solution effectiveness, like power quality costs, typically will vary with the severity of the power quality disturbance. This relationship can be defined by a matrix of "% sags avoided" values. Table III illustrates this concept [22].

Table III
Effectiveness of PQ mitigation techniques

Alternative	Interruption	< 50 % sag	50 – 70 % sag	70 – 90 % sag
BSES (Battery ride through)	100	100	100	100
DVR (50% voltage boost)	0	20	90	100
STS (10 MVA)	100	80	70	50

The probabilistic methods were also used to estimate the optimal custom power device from an economic view. A Monte Carlo simulation was used for this purpose and was presented in [26].

4.3 Financial analysis

Several evaluation methods can be used, according to the company's internal evaluation criteria for investment. The most familiar methods are [27-28]:

i) Payback time (PBT)

The payback time represents the amount of time that it takes for a project to recover its initial cost. The use of the PBT as a capital budgeting decision rule specifies that all independent projects with a PBT less than a specified number of years should be accepted. When selecting from mutually exclusive projects, the project with the shortest payback is to be preferred.

The PBT can be calculated from eq. (1):

$$PBT = \frac{\text{Net investment}}{\text{Net annual return}} \qquad (1)$$

Where net investment is the initial cost (mitigation equipment cost + installation cost) and net annual return is the annual expenses (operation + maintenance) subtracted from the annual benefits.

Although widely used, payback time suffers from several drawbacks. First, PBT does not consider the time-value of money. The second flaw is that payback does not consider the effects of different life-spans of the alternatives, thus penalizing projects that have long potential life-spans. The third drawback is that the accept/reject criterion is often short. For example, many organizations require a 1 to 3 year payback period to consider a cost-saving project and place a higher priority on projects with a shorter payback time.

ii) Net present value (NPV)

The net present value (NPV) of a project indicates the expected impact of the project on the value of the company. Projects with a positive NPV are expected to increase the value of the company. Thus, the NPV decision rule specifies that all independent projects with a positive NPV should be accepted. If NPV is greater than zero the project is valid, since the revenues are enough to pay the interest and recover the initial capital cost before the end of the life of investment. When NPV equals zero, the balance occurs at the end of the life, and the investment is scarcely attractive. When selecting from mutually exclusive projects, the project with the largest positive NPV should be chosen.

The NPV can be calculated from eq. (2):

$$NPV = \sum_{t=0}^{n} \frac{(\text{solution net saving})_t}{(1+r)^t} - C_0 \qquad (2)$$

Where r is the discount rate, C_0 is the initial investment, t is the number of years, and n is the lifetime of the investment.

Some companies apply the NPV only for investments above a certain amount. Typically, these investments have to be approved by the upper management. Below this amount, investments are evaluated using the payback method [29].

Other costs associated with the financial analysis include project engineering expenses of selecting the equipment, purchasing department expenses, freight and receiving expenses, commissioning expenses, and any spare parts requested. This approach is called total system life cycle cost, and should be taken in consideration during the final analysis [30].

5. Proposed methodology

1. A good estimate of the number of short interruptions and voltage sags with different severities is the first step in any financial procedure. Historical survey data, similar available information or case studies (see Table I), data from the utility electrical supplier, will be a good start. In case of lack of data, probabilistic methods may be used.
2. Convert the different sags to a per unit interruption base value, cumulate the summated events in one variable; equivalent number of shutdowns / year.
3. Calculate the average total cost of one shutdown.
4. Multiply the result of step (2) by that of step (3) to calculate the annual cost of shutdown.
5. Investigate the available custom power devices. Get the cost of installation, operation and maintenance

costs, and any available technical and economical data. Tables II and III may be helpful.

6. Instead of investing a small fortune in purchasing the required solution, a bank loan could be more attractive. If the required figure is C, then the annual share for the lifespan of the equipment (n years) with a discount rate of r can be calculated from eq. (3):

$$\text{Yearly share} = \frac{C\,(1 + r * n)}{n} \quad (3)$$

The annualized costs can be calculated based on a 15-year life and an interest rate of 10%.

7. Determine the total annual cost for each alternative, including both the operations and maintenance costs and costs associated with the residual shutdowns (remember that the solutions do not typically eliminate these costs completely as shown in Table III).

8. For solution alternatives, make a comparison with the "No-Mitigation" or "Do-Nothing" case. This is the figure calculated in step (4).

9. The optimum solution will be the device which gives a total annual cost lower than the annual costs associated with the shutdown. Note that if none of the alternatives is lower than the threshold, the "No-Mitigation" will be the most economical action.

10. Discuss and comment on the results.

6. Case study

Alexandria National Refining and Petrochemicals Co. (ANRPC) is a refinery based in Alexandria, Egypt, with an average load of 10 MW, of which 80% are directly connected induction motors at various voltage levels (11, 6.3, 0.4 kV). As the motor torque is directly proportional to the square of the supply voltage, a decrease (sag) to 70% of the rated voltage will cause the motor torque to decrease to 49%, which may not be sufficient for driving the load. In addition, applying out of phase voltages whenever the voltage is restored may result in transient currents and torques of excessive values. To avoid the risk of damage of the motors' shafts during such events, strict protection settings are applied, causing induction motors to trip, either by undervoltage or by overcurrent relays, sometimes by the mechanical protection, and leading to numerous shutdowns.

4. RESULTS

1. A 24 months survey is conducted to investigate the number (frequency) and causes of interruptions and sags. The results of the survey are summarized in Table IV:

Table IV
Site Survey Results

Event	No. of events (2 years)
Interruption	2
Sag magnitude < 75% pu & Sag duration > 1.5 s	4
Other minor sags	25
Total	31

2. To calculate the annual no. of equivalent events, the settings of the undervoltage protection relay were adjusted to trip for events below 75% of the nominal voltage for durations of 1.5 seconds. Sags with magnitude and duration more than these settings cause the protection relay to trip leading to the process shutdown. These sags will be weighted the same as the interruptions. Sags resulting in minor or partial effects are weighted 20% of the base event.

Equivalent number of shutdowns / year =
$(1 * 2 + 1 * 4 + 0.2 * 25)/2 = 5.5$

3. The cost of one shutdown is estimated by the company financials to be 50,000 US $ per event.

4. The annual cost of shutdowns = 5.5 * 50,000 = 275,000 US $. This is the value to be compared with the annual costs of solution alternatives.

5. In this study, the following custom power devices will be investigated: the DVR with 50% boosting capability, the STS with 10 MVA rating, and the BSES with batteries. Their technical and economical data are summarized in Table V.

Table V
Custom Power Devices Data

Feature	DVR	STS	BSES
Interruption Mitigation	0	90%	100%
Sag voltage > 75%	100%	70%	100%
Sag voltage < 75%	75%	80%	100%
Requirements	-	Another feeder	-
Initial cost (US $)	750,000	600,000 + 400,000 for additional feeder (if needed)	1,500,000
Annual maintenance and operation costs	37,500	30,000	225,000

Note that the DVR cannot mitigate for interruptions. The STS will transfer the load to another feeder, and the high percentage of its capability depends on the situation of the other feeder at the sag instance. Interruptions and severe sags are likely to occur due to internal faults or faults near the substation. Costs of the alternatives are calculated from Table II.

6. To calculate the annual cost of solution, apply eq. (3) for n=15 and r = 10% to get the first row of table VI.

7. For each alternative, add to Table VI a second row for the operation and maintenance costs, and a third row for the cost of unmitigated events.

Table VI
Total cost for different alternatives

	DVR	STS	STS (another feeder needed)	BSES
Annual solution cost In US $	125,000	100,000	166,666	250,000
Annual operation and maintenance costs	37,500	30,000		225,000
Annual costs of unmitigated events	75,000	62,500		0
Total costs	237,500	192,500	259,166	475,000

8. Comparing the results of Table VI with that of the annual costs of shutdown, it can be better done using the comparison chart of Fig. 6

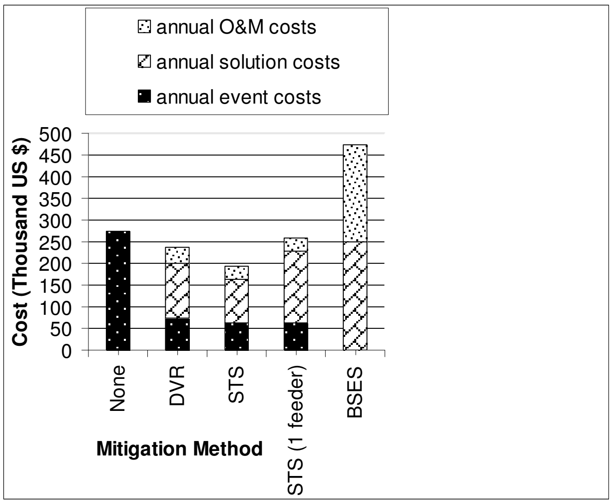

Fig. 6 Comparison chart

9. From the comparison results, we can conclude that the best solution for this particular case study is the implementation of the STS, provided that another feeder already exists. If there is only one feeder available, then the best solution in this case is the DVR.

10. Discussions and comments are presented in the next section.

7. Discussions and comments:

The results obtained from this specific case study cannot be generalized by any means. Each case should be studied separately according to the proposed procedure.

We can have a premium quality of power with no sags or interruptions using the BSES, but this solution is not economic. Its costs are higher than that of the financial losses due to such events.

The STS and the DVR show justified economical value, however the plant in this case will suffer from a fewer number of voltage sags and interruptions. These solutions are not "cure-all". The BSES may be the perfect solution for other applications, where the cost of shutdown may be very expensive.

There is a certain degree of uncertainty in the figures used throughout the study. Some "hidden costs" may arise. For example, some personnel in the field may interpret a voltage sag affecting only the lighting as a power failure, and start an emergency shutdown. The blinking lights may cause injuries to the personnel, may have the personnel work under tension, may lead to lack of confidence in the electrical department, and many other "soft costs".

Apart from the estimated financial losses due to the process shutdown (which are based on the expected number of events through the next 10-15 years) and which is assumed to be constant, the costs of the solution alternatives are also susceptible. For example, the cost of the land (if existed !) or the footprint, any training costs for the unqualified personnel who will deal with the new technology, any mis-operation of the equipment, the cost of unmitigated events during the equipment maintenance.

In the case of requiring another feeder for applying the STS, the estimated figure is based on personal experience and may vary according to the costs of cables, digging and laying, road rites, switchgear modification, and re-engineering the system.

Some probabilistic methods might be necessary in similar studies, at least as a means to validate the results. This topic would be addressed in a future work.

Managers and decision makers often want some indices, payback rates, added values of the investment, etc. In this sight some simple calculations using eq. (1) & (2) may be helpful yielding the results of Table VII:

Table VII
Economical measures for solution alternatives

	DVR	STS	STS requiring another feeder	BSES
PBT (years)	4.6	3.3	5.5	30
NPV (US $)	485,975	788,095	388,095	-1,119,700

It can be easily shown that these results enhance the results of the proposed procedure. The best solution for this case is the STS (provided that two feeders are available) since it results in the minimum Pay Back Time and the maximum positive Net Present Value. If only one feeder is available, the DVR will be the best solution. The BSES needs 30 years to break positive (remember that the lifetime of the equipment is estimated by 15 years only) and its NPV is negative.

8. Conclusions

The increasing interest in the Power Quality studies in recent years is attributed not only to technical issues, but also to the huge financial losses associated with poor quality of the delivered power. Two of the most relevant problems are voltage sags and short interruptions. These events are caused mainly by system faults and therefore cannot be totally eliminated. Industrial customers seeking for a cost-effective mitigation solution are faced by several custom power devices, all requiring large investments, and probably will not stop all the process shutdowns due to these events.

In this study, a methodology was proposed to help the decision maker to compare the solution alternatives from a techno-economic perspective. The annual cost of voltage sags and interruptions is calculated first, then compared with the annualized solution alternatives costs to select the best solution for each case study.

Future work is still required to address the uncertainty in the estimated values of the parameters used throughout the study.

References

1. Bollen, M.: *Understanding Power Quality Problems: Voltage Sags and Interruptions*. Wiley-IEEE Press, New York, 1999.
2. Ghosh, A. and Ledwich, G.: *Power Quality Enhancement Using Custom Power Devices.* Springer, 2002.
3. IEEE Std 1159-2009, *IEEE Recommended Practice for Monitoring Electric Power Quality.* 2009.
4. IEC 61000-2-1. *Electromagnetic Compatibility (EMC) – Part 2: Environment – Section 1: Description of the Environment – Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signalling in Public Power Supply Systems.* 1990.
5. Baggini, A.: *Handbook of Power Quality*. John Wiley & Sons, Ltd, London, 2008.
6. Elmendorf, F., King, L. and Ingram, M.: *Correlating Voltage Sags with Line Faults and Lightning*. IEEE Computer Applications in Power, Apr. 2001, pp. 22-24.
7. McGranaghan, M., Muller, D. and Samotyj, M.: *Voltage Sags in Industrial Systems.* IEEE Trans. Industry Applications, Vol. 29, No. 2, Mar. 1993, pp. 397-403.
8. Lamoree, J., Muller, D., Vinett, P., Jones, W. and Samotyj, M.: *Voltage Sag Analysis Case Studies.* IEEE Trans. Industry Applications, Vol. 30, No. 4, Jul. 1994, pp. 1083-1089.
9. ANSI/IEEE Std 1250-2002, *IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances*. 2002.
10. IEEE Std 493-2007, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (Gold Book).* 2007.
11. Sannino, A., Miller, M. and Bollen, M.: *Overview of Voltage Sag Mitigation.* In Proc. IEEE Power Engineering Society Winter Meeting, Singapore, 23-27 Jan. 2000, pp. 2872-2878.
12. Hingorani, N.: *Introducing Custom Power.* IEEE Spectrum, June 1995, pp. 41-48.
13. Sabin, D. and Sannino, A.: *A Summary of the Draft IEEE P1409 Custom Power Application Guide.* In Proc. IEEE Power Engineering Society Transmission and Distribution Conf. and Exposition, Dallas, USA 7-12 Sep. 2003, pp. 1-6.
14. Benachaiba, C. and Ferdi, B.: *Voltage quality improvement using dynamic voltage restorer.* Electrical Power Quality and Utilization Journal, Vol. 14, No. 1, 2008, pp. 39-46.
15. Woodley, N., Morgan, L. and Sundaram, A.: *Experience with an Inverter-Based Dynamic Voltage Restorer.* IEEE Trans. Power Delivery, Vol. 14, No. 3, July 1999, pp. 1181-1186.

16. Affolter, R. and Connell, B.: *Experience with a Dynamic Voltage Restorer for a critical manufacturing facility*. In Proc. IEEE Power Engineering Society Transmission and Distribution Conf. and Exposition, Dallas, USA, 7-12 Sep. 2003, pp. 937-939.
17. Middlekauff, S. and Collins, E.: *System and Customer Impact: Considerations for Series Custom Power Devices*. IEEE Transactions on Power Delivery, Vol. 13, No. 1, January 1998, pp. 278-282.
18. Jipping, J. and Carter, W.: *Application and Experience with a 15 kV Static Transfer Switch*. IEEE Trans. Power Delivery, Vol. 14, No. 4, Oct. 1999, pp. 1477-1481.
19. Sannino, A.: *STS and Induction Motors*. IEEE Industry Applications Magazine, July 2003, pp. 50-57.
20. Sannino, A., Svensson, J. and Larsson, T.: *Power Electronic Solutions to Power Quality Problems.* Electric Power Systems Research, Vol. 66, 2003, pp. 71-82.
21. Chowdhury, B.: *Power Quality.* IEEE Potentials, Apr. 2001, pp. 5-11.
22. McGranaghan, M. and Roettger, B.: *Economic Evaluation of Power Quality*. IEEE Power Engineering Review, Feb. 2002, pp. 8-12.
23. Sullivan, M., Vardell, T. and Johnson, M.: *Power Interruption Costs to Industrial and Commercial Consumers of Electricity*. IEEE Trans. Industry Applications, Vol. 33, No. 5, Nov. 1997, pp. 1448-1458.
24. Milanovic, J. and Gupta, C.: *Probabilistic Assessment of Financial Losses due to Interruptions and Voltage Sags*. IEEE Transactions on Power Delivery, Vol. 21, No. 2, Apr 2006, pp. 918-932.
25. Hertem, D., Didden, M., Driesen, J. and Belmans, R.: *Choosing the Correct Mitigation Method Against Voltage Dips and Interruptions: A Customer-Based Approach*. IEEE Transactions on Power Delivery, Vol. 22, No. 1, January 2007, pp. 331-391.
26. Maitra, A., Gaiiad, A. and Short, T.: *Assessing Financial Feasibility of PQ Improvement Devices Using Monte Carlo Simulations*. In Proc. 8th Intemational Conference on Probabilistic Methods Applied to Power Systems, Iowa State University, Ames, Iowa, USA, September 2004, pp. 569-574.
27. Baggini, A. and Bua, F.: *Investment Analysis for Power Quality Solutions*. Leonardo Power Quality Initiative (LPQI): Power Quality Application Guide, Chapter 2.5, June 2004.
28. Thasananutariya, T., Chatratana, S. and McGranaghan, M.: *Economic evaluation of solution alternatives for voltage sags and momentary interruptions*. Electrical Power Quality and Utilisation Magazine, Vol. 1, No. 2, Dec. 2005, pp. 17-26.
29. Didden, M., Belmans, R. and D'haeseeler, W.: *Persuading Consumers to Invest in Voltage Sag Mitigation Devices*. In Proc. EPRI Power Quality Assurance (PQA) Conf., Portland, USA, June 2002, pp. 1-12.
30. Han, J. and Jang, G.: *Probabilistic life cycle cost analysis of custom power devices for voltage sags and interruptions mitigation*. In Proc. IEEE Transmission & Distribution Conference & Exposition: Asia and Pacific, Seoul, Korea, Oct. 2009, pp. 1 - 4

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