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Economic Evaluation of Solution Alternatives for Voltage Sags and Momentary Interruptions

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Summary: **This paper proposes a practical method for economic evaluation of different alternatives to improve the performance of industrial facilities for voltage sags and momentary interruptions. Different technologies for solving voltage sag problems are discussed (both utility and customer solutions) and a procedure for evaluating the economics of the different alternatives is described. The concept of weighting factors to account for different levels of equipment sensitivity and customer costs as a function of the disturbance severity is introduced. This method allows for convenient evaluation of voltage sag impacts along with momentary interruption impacts. The economic analysis uses standard financial measures, such as the payback period, net present value (NPV), and internal rate of return (IRR) to assess the alternatives. The methodology is illustrated using a case study of voltage sag performance improvement alternatives at an industrial customer located in the Metropolitan Electricity Authority (MEA) service area.**

Key words:
power quality
power distribution
power conditioning
economic

1. INTRODUCTION

Voltage sags and momentary interruptions are the most significant power quality problems encountered by many industrial and commercial customers. Whether or not a voltage sag causes a problem will depend on the magnitude and duration of the sag and on the sensitivity of the equipment [1]. Important equipment that may be sensitive to voltage sags includes adjustable speed drive controls, motor starters contactors, programmable logic controllers, robotics, controller power supplies, and control relays. This equipment is employed in applications that are critical to an overall process, which can lead to very expensive downtime when voltage sags occur.

Because of the impacts to important customers, utilities strive to improve the voltage sag performance of the power system by reducing the number of faults that occur in both transmission and distribution systems. However, faults that are the major cause of voltage sags cannot completely be eliminated. Therefore, customers often must employ power conditioning equipment to improve the ride-through capability for sensitive or critical loads.

This paper describes a practical method of determining the most cost-effective solution for voltage sag and momentary interruption problems. The voltage sag mitigation techniques that can be employed are described and the best solution is determined using economic analysis. The overall analysis includes the costs of the voltage sag problem (cost to customers for disruptions caused by the voltage sags) and the costs of the mitigation alternatives.

2. VOLTAGE SAG MITIGATION SOLUTIONS

The voltage sag mitigation solutions can be implemented by applying the power conditioning devices at several different levels, as shown in Figure 1 [2]. Large power conditioning options that can protect large portion (or all) of facility have higher costs. On the other hand, designing solutions for specific equipment or processes requires detailed knowledge of the process equipment and the equipment susceptibility to disturbances. In fact, finding the best solution must involve all the parties that are affected; the power utility company, the end-user, and the equipment manufacturers.

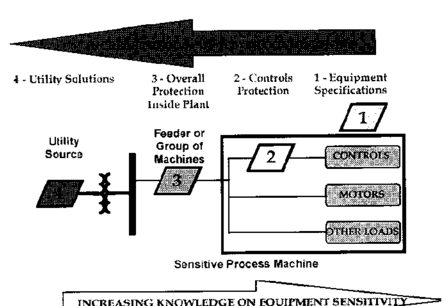


Fig. 1. Alternatives of voltage sag mitigation solutions at different levels

The solution can be implemented inside the facility (including equipment modification options) or in the supply system.

3. UTILITY SOLUTIONS

Utility options to solve the voltage sag problem are usually limited. They can include the investments to reduce the number of faults (even this may be out of the control of the distribution company if the faults occur on the transmission system), system changes to reduce the impact of the faults in specific customers, or the addition of technologies to protect customers or groups of customers (custom power).

3.1. Fault Prevention

Most voltage sags affecting industrial processes are caused by faults on the supply system. Obviously, reducing the number of faults will reduce both voltage sags and momentary interruptions.

Fault prevention investments in power distribution systems include tree trimming, insulator washing, adding line arresters, adding animal guards [3], and preventive maintenance before rainy season [4]. Replacing bare overhead conductor with insulated conductor [4], [5] or underground circuits can improve performance for faults caused by lightning, trees, and animals.

Voltage sags are caused by faults at the transmission level as well as the distribution level. Transmission system fault performance (especially for lightning-caused faults) can be improved through improved grounding, higher insulation strength, and arrester applications [6].

3.2. Power System Operation Improvement

1) *Reducing fault clearing time*: This solution results in reduce sag duration and leads to less severe voltage sags [5]. Total fault clearing time is a combination of the circuit breaker clearing time and relay operating time. Reduction of fault clearing time for faulted feeder circuits can be accomplished with the instantaneous trip function for overcurrent relays and reclosers rather than delayed tripping [4]. However, this must be coordinated with branch fuse operating characteristics in order to avoid increasing the number of momentary interruptions.

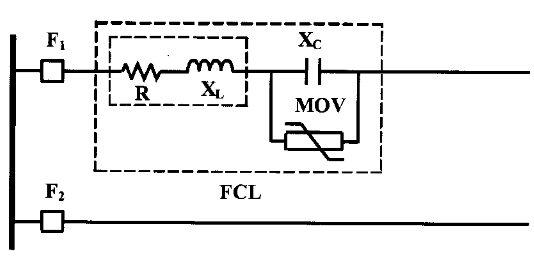


Fig. 2. Basic components of fault current limiter

2) *Modifying system configuration*: Voltage sag performance can be improved by reducing the "area of vulnerability" [7]. On transmission systems, it may be possible to improve voltage sag performance through system topology modifications, such as opening tie breakers between different parts of the system. On distribution systems, using open tie breakers for multiple bus sections can reduce exposure to faults on feeders supplied from adjacent buses. In either case, these changes must be considered along with possible reliability impacts. Momentary interruption performance can be improved with express feeders for dedicated customers.

3) *Applying fault current limiter (FCL)*: A FCL must be installed immediately downstream of the feeder's circuit breaker. One possible design consists of a series connection of inductance (L) and capacitance (C) tuned to resonate at the fundamental frequency. An MOV arrester is connected in parallel with the capacitor [8] to limit the current during fault conditions, as shown in Figure 2. When a fault occurs on any part of feeder F_1, the fault current flows through the series L-C circuit resulting in an overvoltage across the capacitor. The voltage rating of MOV arrester is specified to control this overvoltage, effectively bypassing the capacitor during the fault. The fault current is limited by the impedance of the reactor in series L-C circuit [9].

3.3. Custom Power

Custom power devices are applied in medium-voltage distribution systems to protect an entire facility or a group of sensitive loads in a plant [10]. Custom power solutions can be implemented by the power utility or by the end-user [11]. In this paper, three different technologies of custom power devices are considered: static series compensator, backup storage energy supply, and source transfer switch.

1) *Static series compensator (SSC)*: The static series compensator is a waveform synthesis device based on power electronics that is series-connected directly into the utility primary feeder by means of a set of single-phase insertion transformers [10], [11]. This device does not protect a load against interruptions and is generally limited in its design to providing correction for voltage sags that have a minimum voltage no lower than about 50% of nominal voltage. An example of this device (a dynamic voltage restorer – DVR) is shown in Figure 3.

The DVR uses a voltage source converter (VSC) connected in series with the protected load (through an insertion transformer for medium voltage applications) to compensate amplitude and phase angle of the voltage applied to the load. The dc capacitor between the charger and the VSC serves as an energy buffer, generating and absorbing power during voltage sags and voltage swells, respectively [12]. This process enables the voltage, as seen by the load, to be of the desired magnitude whenever disturbances occur upstream [13].

2) *Backup storage energy supply (BSES)*: This device disconnects a protected load from the utility supply within milliseconds after a disturbance and supplies the entire load using stored energy and appropriate power electronics [10]. Figure 4 shows the main components of a BSES. When a disturbance in the utility supply is detected, an isolation switch will operate to disconnect the protected load from the utility supply in 4 ms or less [14]. Then the dc stored energy is supplied to the protected load through a voltage source converter that transforms the dc energy to 50 or 60 Hz ac power. The transformer is used for interconnection at medium voltage levels. Typical sources for stored energy are batteries, flywheels, or superconducting magnetic coils. The energy storage device is charged to normal levels by the charger after it discharges. The level of energy storage needed will depend on the durations of momentary interruptions that can be expected. For instance, a flywheel system might provide backup for 10 seconds, which would be sufficient for most momentary interruption durations.

3) *Static transfer switch (STS)*: The medium-voltage STS is designed to provide a whole facility voltage sag and interruption protection when a dual distribution feeder service is available. Figure 5 shows the circuit of a double static switch configuration, feeding a common load bus. When a disturbance occurs on the primary supply, the STS transfers the whole facility load to the alternate feeder in less than a half cycle to minimize the impact on critical and sensitive loads. The effectiveness of the solution will depend on how independent these two supplies are from each other [10]. It is best if primary and alternate feeders are fed from two different distribution substations.

4. END-USER SOLUTIONS

The voltage sag solutions for customer side are classified into two facility-level solutions (or groups of loads) and equipment-level solutions.

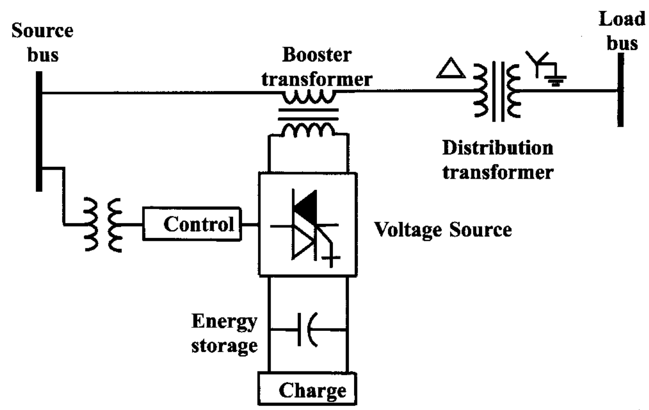


Fig. 3. Basic configuration of DVR

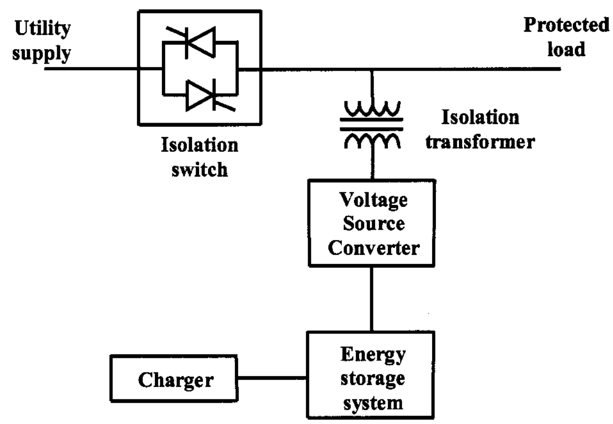


Fig. 4. Backup storage energy supply components

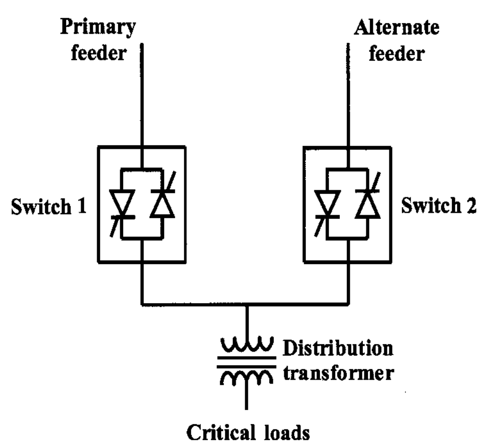


Fig. 5. One-line diagram of a double static switch configuration

4.1. Facility-Level Solutions

1) *Low-voltage static series compensator (SSC)*: An LV static series compensator is a waveform synthesis device based on power electronic that is series-connected directly "to" the LV distribution circuit [10]. The working principle of a low-voltage SSC device is similar to a medium-voltage DVR as described previously, except an injection transformer is generally not needed.

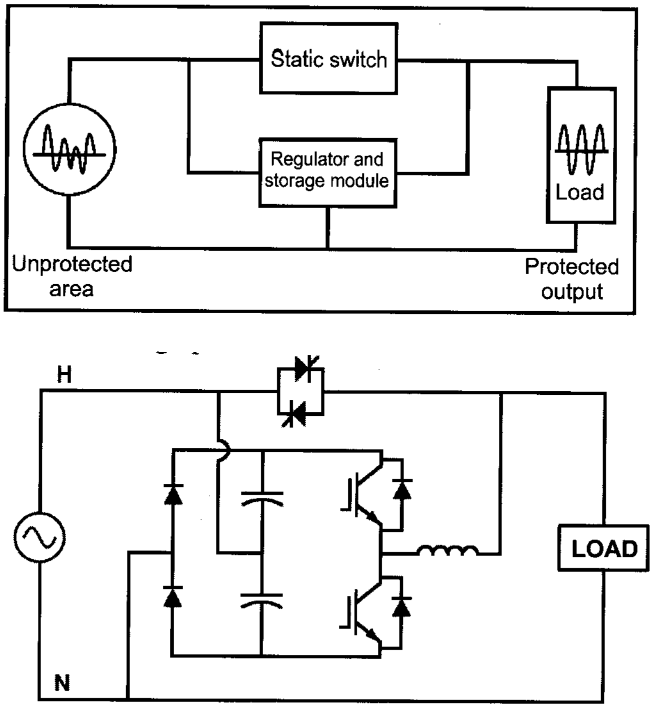


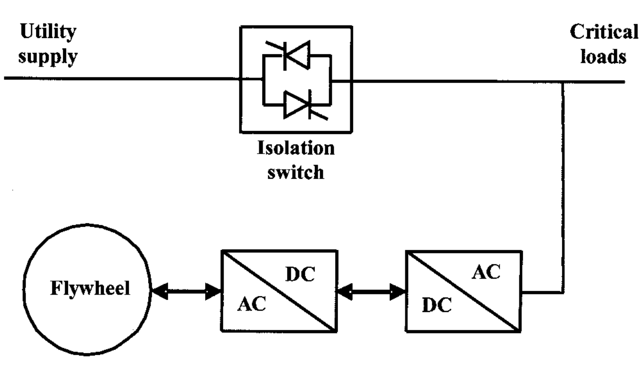
Fig. 6. One-line diagram and per phase configuration of a dynamic sag corrector (DyS"C")

2) *Flywheel with UPS System*: The flywheel with UPS integrates the function of a motor, flywheel rotor and generator into a single integrated system (Figure 7). Modern flywheels can provide energy storage for many seconds of ride through support in the event of a disturbance. This solution provides full ride through support for voltage sags and interruptions and the duration is dependent on the size of the flywheel relative to the load [17], [18]. The advantage of the flywheel is reduced maintenance and size compared to battery-based systems.

Figure 6 shows an example of a low voltage SSC, called a Dynamic Sag Corrector (DySC). The DySC compares the load voltage to a reference waveform and calculates a missing voltage. This missing voltage is injected by the regulator and storage module. The DySC is generally sized to provide full boost of the voltage for voltage sags down to 50% of nominal value and to provide very short duration backup for more severe events using capacitor energy storage [15]. Additional capacitive energy storage can be provided to increase the ride-through for momentary interruptions up to 12 cycles [16].

Other technologies for series voltage injection at LV can also be used and are similar to the concepts described previously for the medium voltage DVR. Typically, a DVR would be designed to handle incoming voltages as low as 40% for a period of up to about one second. This performance can protect the equipment for almost 90% of the voltage sags for typical facilities [17].

Fig. 7. Flywheel with UPS system



4.2 Equipment-Level Solutions

Equipment-level solutions for voltage sags are designed to provide ride through support for critical elements of equipment, such as the control systems, that may determine the overall response of the process during voltage sags. Some of the important approaches are discussed here.

1) *Voltage Dip Proofing Inverter (DPI)*: When a voltage sag that drops below an adjustable threshold is detected, the incoming supply to the device is opened and the DPI supplies a square-wave output to the load for about 1 to 3 s. The amount of time that the load will be supplied can be calculated on the basis of real power and the energy storage of the device [19]. It is an off-line device with a transfer time less than 700 ms [17]. The DPI consists of a static switch to quickly disconnect the normal supply and an inverter to convert energy stored in a capacitor bank to ac for the load being protected. Figure 8 shows block diagram of DPI. The DPI technology is very appropriate for many control circuits.

2) *Constant Voltage Transformer (CVT)*: The CVT is a ferroresonant transformer that maintains two separate magnetic paths with limited coupling between them. The output contains a parallel resonant tank circuit and draws power from the primary to replace power delivered to the load. The transformer is designed so that the resonant path is in saturation while the other is not. As a result, changes in the primary voltage are not reflected as changes in the saturated secondary voltage. These devices will allow for much better voltage sag ride-through if they are sized to at least two and a half times the nominal VA requirement of the load. Oversized in this manner, CVTs can supply at least 90% of nominal voltage when the input voltage has dropped to as low as 40% of nominal value [19]. The CVT provides voltage regulation for both voltage sags and voltage swells [10]. The basic construction of CVT is shown in Figure 9.

3) *Uninterruptable Power Supply (UPS)*: The two basic types of UPS, off-line (or stand-by) and on-line, are shown in Fig.10 (a) and (b) respectively. The off-line UPS is used when minor disturbances in the supply associated with the changeover from normal to backup power will not cause problems with the load. In the normal configuration, the load is powered from the supply system. When a disturbance is detected, the automatic transfer switch (ATS) operates to transfer load to the battery. To ensure continuity of operation for critical load the transfer time should not be more than 4 ms [20]. The on-line UPS supplies power to the load continuously. At the same time the battery is also charged. If the main supply fails, the load is supplied from the battery automatically.

4) *Coil Hold-In Devices*: These devices work on the principle of injecting a rectified DC voltage from the remaining voltage during a voltage sag to keep a contactor coil energized [17]. They are designed to mitigate the effects of voltage sags on individual relays and contactors. Typically, the coil hold-in device is connected in line with the supply to the relay or contactor [19]. The rating of the device is based on the resistance of the coil, which usually decreases with the size of the relay or contactor [10]. This can be a very economical way to prevent unnecessary dropout of contactors during voltage sags. They provide ride-through for the voltage drop as low as 25% voltage and up to 20 cycles [17].

5. ECONOMIC EVALUATION PROCEDURE

In general, the economic evaluation of voltage sags can be divided into four steps as follows [21]:

Step 1: Characterize the system voltage sag performance. Voltage sag performance due to transmission and distribution faults is determined. The summation of the expected voltage sags from each level is the annual expected number of voltage sags at a particular customer. The annual number of momentary interruptions from the specific distribution circuit is also calculated [7].

Step 2: Estimate the cost associated with voltage sags and interruptions. Normally, an interruption causes all processes in the plant that are not protected to shutdown. Voltage sags may cause some portion of the process to shut down, depending on the severity of the voltage sag. The severity levels of voltage sags are characterized for economic analysis by multiplying the base interruption cost with a weighting factor representing the relative impact of the voltage sag compared to a momentary interruption [21]. For example, if the base cost associated with an interruption is 1.0, a voltage sag to 0.5 per unit that causes 80% of the economic impact of the momentary interruption would have a weighting factor of 0.8.

When the weighting factors are applied to the annual expected numbers of voltage sags and momentary interruptions, the costs of these events are expressed in per unit of the cost

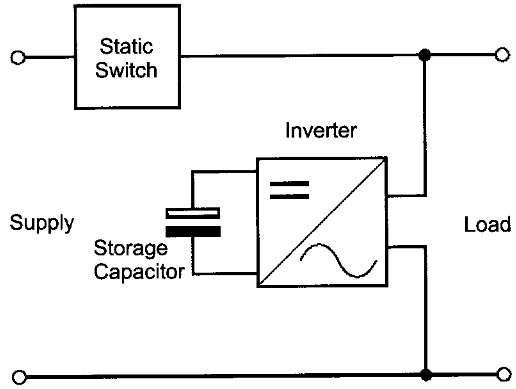


Fig. 8. DPI block diagram

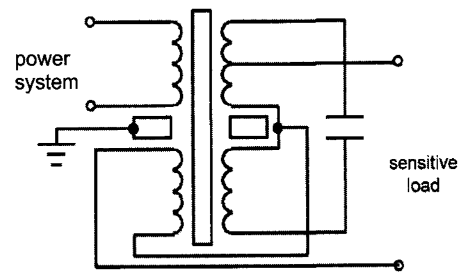
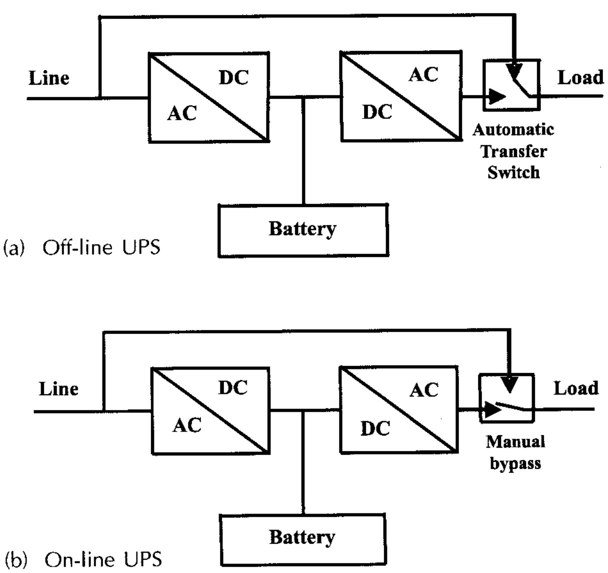


Fig. 9. Typical circuit for a ferroresonant transformer



(a) Off-line UPS

(b) On-line UPS

Fig. 10. Uninterruptible power supply

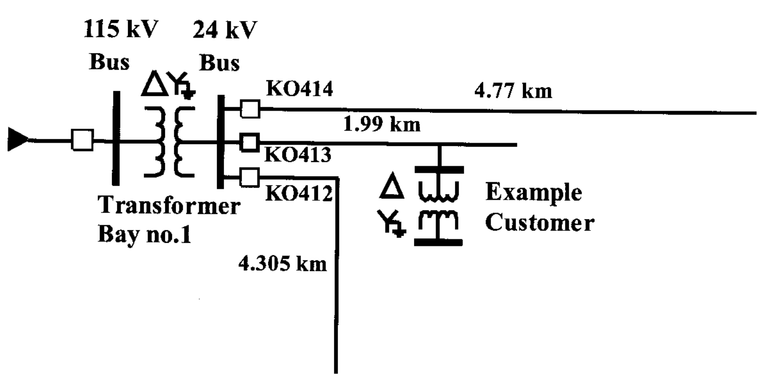


Fig. 11. One-line diagram of distribution supply system of the example customer

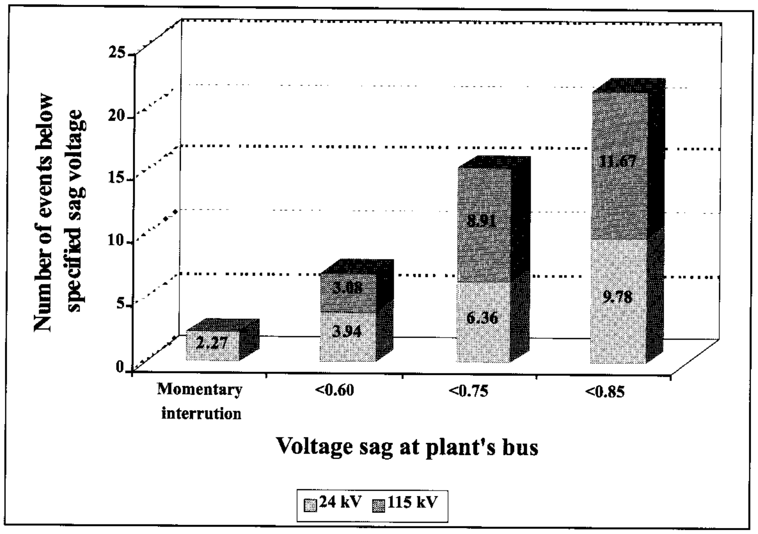


Fig. 12. Annual expected number of voltage sag and momentary interruption

of a momentary interruption. The weighted events can then be summed, and the total is the total cost of all the events expressed in number of equivalent momentary interruptions [21].

Step 3: Characterize the solution alternatives in term of costs and effectiveness. The cost of equipment used to protect the sensitive loads from voltage sags includes initial and operation costs. The initial cost is the cost of equipment and installation cost. The operation cost is the ongoing operating and maintenance costs, sometimes estimated as a percentage of the initial cost.

In addition, the solution effectiveness of each alternative must be quantified in term of the performance improvement that can be achieved. Typically, the solution effectiveness will also vary with the severity of the voltage sag [21].

Step 4: Perform the economic analysis. In this step, the payback period, net present value and internal rate of return of each alternative are determined. The net present value and internal rate of return of the different options for improvement of voltage sag performance are compared. The option that gives the highest net present value and internal rate of return is usually the best choice for most businesses.

6. FINANCIAL ANALYSIS

6.1 Payback Period

The payback period is the number of months of benefits required for the project to break even [22]. The payback time can be estimated by the following equation:

Table 2 Total equivalent interruptions

$$Payback(months) = \frac{net\ investment}{net\ annual\ return} \times 12 \quad (1)$$

where net investment is the initial cost (mitigating equipment cost + installation cost) and net annual return is the ongoing annual expenses subtracted from the annual benefits. Many industrial companies look for projects with a payback of less than 1–2 years in order for them to be considered. This is equivalent to a 50–100% return rate [23].

6.2. Net Present Value (NPV)

This is the present value of the expected net cash flows of an investment, discounted at cost of capital and subtracted from the initial cash outlay of the project. The NPV is calculated by the following formula [23], [24]:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - C_0 \quad (2)$$

where CF_t is the net cash flow at time t, C_0 is the initial investment, r is the cost of capital (discount rate), t is the number of years, and n is the lifetime of the investment. The business should have a target cost of capital. Using this cost of capital and the selected project lifetime, if the NPV is positive the project should be accepted.

6.3. Internal Rate of Return (IRR)

The IRR is the discount rate that makes the present value of a project's cash flows equal to its initial investment. The equation used to calculate the IRR is:

$$\sum_{t=0}^{n} \frac{CF_t}{(1+R)^t} - C_0 = 0 \quad (3)$$

where R is the internal rate of return. The project with an IRR greater than the cost of capital should be accepted; otherwise it should be rejected [23].

7. APPLICATION EXAMPLE

A particular industrial plant located in Bangpu industrial estate has a utilization voltage of 416 V and a peak demand of 1500 kVA. The plant is supplied by a 2000 kVA distribution transformer from a 24 kV primary feeder # KO413 shown in Figure 11. A 2 x 60 MVA, 115-24 kV distribution substation called Kotor supplies power to this customer. The customer is 1.48 km from the substation. The details of the transmission supply system for this industrial plant were described in [7]. A 1 MVA critical load in this customer facility is sensitive to voltage sags. The mitigation solutions for improving the voltage sag performance of this plant are analyzed to illustrate the economic assessment procedure.

7.1. Economic Evaluation

1) *Annual expected number of voltage sags and momentary interruptions*: According to [7], the annual expected number of voltage sags below 60%, 75%, 85% and momentary interruptions that occur at plant location are 7.02, 15.27, 21.45 and 2.27 respectively (see Figure 12 showing the split between events caused by faults on the 24 kV system and events caused by faults on the 115 kV transmission system).

2) *Estimate the costs associated with voltage sags and interruptions*: The cost of an interruption for an industrial customer in MEA's service area is $4663 [25]. The base cost for this example was developed from the six types of damages, namely salary or work payment, cost of loss of profit opportunity, overtime payment, cost of loss of raw material, cost of restarting the process, and cost of damaged equipment. Table 1 shows the weighting factors which are used to estimate the relative impact of voltage sags on the industrial customer costs. These weighting factors are applied to the expected voltage sag and momentary interruption performance to determine the total cost impact on the plant in Table 2.

With a cost per interruption of $4663, the total costs associated with voltage sags and interruptions are $63,182 per year.

3) *Characterize the solution alternatives in terms of costs and effectiveness*: Table 3 provides a summary of initial costs and operation costs assumed for some of technologies used to improve performance for voltage sags and interruptions. These costs are very system dependent so it is difficult to provide general numbers. However, the values in Table 3 provide reasonable estimation for this example analysis.

For control level protection, a dynamic sag corrector option is evaluated (other controls protection options could be used with similar costs). The UPS, flywheel and dynamic sag cor-

Table 1 Weighting factors for different voltage sag magnitudes

Event category	Weighting for economic analysis
Interruption	1.0
Sag with min. voltage below 60%	0.85
Sag with min. voltage below 75%	0.40
Sag with min. voltage below 85%	0.15

Event category	Weighting for economic analysis	No. of event per year	Total equivalent interruptions
Interruption	1.0	2.27	2.27
Sag with min. voltage below 60%	0.85	7.02	5.97
Sag with min. voltage below 75%	0.40	15.27	6.11
Sag with min. voltage below 85%	0.15	21.45	3.22
Total			17.56

Table 3 Cost of the mitigation technologies

Alternative category	Initial cost ($)	Operation cost (% of initial cost per year)
Controls protection level (<10 kVA)		
CVTs	1000/kVA	1
UPS	500/kVA	2.5
Dynamic sag corrector	250/kVA	0.5
Machine protection level (10-500 kVA)		
UPS	500/kVA	1.5
Flywheel	500/kVA	0.7
Dynamic sag corrector	200/kVA	0.5
Facility protection level (0.5-10 MVA)		
UPS	400/kVA	1.5
Flywheel	400/kVA	0.5
DVR (50% voltage boost)	250/kVA	0.5
Static switch (10 MVA)	600,000	0.5
Fast transfer switch (10 MVA)	150,000	0.5

Table 4. Effectiveness of the mitigation technologies (% of events that would be corrected by the technology)

Mitigation solution technologies	Interruption (%)	Sag with min. voltage below 60% (%)	Sag with min. voltage below 75% (%)	Sag with min. voltage below 85% (%)
Dynamic sag corrector (controls)	0	30	80	100
Dynamic sag corrector/DVR	0	30	90	100
Flywheel ride through technologies	70	100	100	100
UPS (battery ride through technologies	100	100	100	100
Static switch	100	80	75	50
Fast transfer switch	80	75	65	40

Table 5. Economic analysis results

Mitigation solution technologies	Payback period (year)	NPV ($)	IRR (%)
Dynamic sag corrector (controls protection)	5.57	-25,396.77	7.33
Dynamic sag corrector (Machine protection)	4.17	86,242.69	20.17
Flywheel ride through technologies	6.65	-34,338.45	8.21
UPS (battery ride through technologies	6.72	-38,942.46	7.97
Static switch	10.22	-217,487.72	-0.39
Fast transfer switch	2.82	160,280.48	33.42
Fast transfer switch with backup feeder charge	10.56	-57,049.17	-0.99

rector are evaluated for machine-level protection (based on the 1 MVA of equipment that requires protection). At the system level, a static switch and a fast transfer switch (based on vacuum breaker technology) are considered. The expected effectiveness of these options is shown in Table 4.

4) *Economic analysis*: The alternatives are compared by determining the new total costs for each alternative after correction (remaining costs of the disturbances plus the ongoing operation and maintenance costs associated with the solution technology). The annual savings are determined by subtracting the new total costs from the base case costs. These savings are used along with the initial costs of each solution to calculate the appropriate financial indices, as summarized in Table 5. A cost of capital equal to 10% and a 10 year lifetime is assumed for these calculations.

7.2. Result Analysis

The dynamic sag corrector (machine protection) and fast transfer switch both have a positive NPV for this application. The fast transfer switch has the highest NPV value. However, this solution assumes that a backup feeder is available and capable of handling the additional load in case there is a problem with the primary feeder. The economic analysis did not include any charge for the availability of a backup feeder. An additional charge for the backup feeder is estimated to be $38,906 per year. With this additional cost included, the fast transfer switch is not an attractive option. Thus, machine-level protection using a technology like the dynamic sag corrector is shown to be the most attractive option for this example. The investment will return in 4.17 years and give the NPV and IRR of $86,242.69 and 20.17% respectively.

8. CONCLUSION

Voltage sags and momentary interruptions are significant problems for many industrial facilities. They can cause process interruptions that have very high costs. Options for improving the performance of the facility during momentary interruptions and voltage sags should be considered for these facilities based on traditional engineering economics principles.

The economic analysis should include the full range of options – both utility-side solutions and customer-side solutions. The evaluation requires an understanding of the costs of disturbances to the facility. A method which includes voltage sags in the evaluation using weighting factors for the relative costs compared to momentary interruptions was presented. The analysis also requires an understanding of the costs and performance characteristics of the possible solutions. These will vary from site to site but example characteristics were provided as a basis of preliminary evaluations for many facilities.

The evaluation also requires an understanding of the expected voltage sag and momentary interruption performance from the supply system. This data must be obtained from the supply utility based on historical performance and expected performance in the future (taking into account system changes, investments, etc.).

The economic assessment procedure for evaluation of solution alternatives was illustrated with an example. The results of the analysis help put the technologies in perspective by comparing them on a common basis of NPV and IRR values.

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