AUSTRALIAN POWER QUALITY AND RELIABILITY CENTRE

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Australian Power Quality and Reliability Centre

Voltage Sag Mitigation

Technical Note 11
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Endeavour Energy

UNIVERSITY OF WOLLONGONG AUSTRALIA

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1. Executive Summary

This technical note discusses voltage sags including characterisation, causes, measurement and financial impact. Techniques which may be utilised to mitigate voltage sags are described and the advantages and disadvantages of each technology are discussed. It should be noted that the voltage sag mitigation techniques examined are limited to solutions involving the use of equipment designed for this task at the plant/equipment level. Other mitigation strategies such as network improvement along with improving equipment immunity have not been considered. Finally a comparison of the costs of each voltage sag mitigation technology is given.

2. Introduction

2.1. What is a Voltage Sag?

A voltage sag, sometimes known as a voltage dip, is a short term reduction in the rms voltage. The IEC electrotechnical vocabulary, IEC 60050 [1], defines a voltage sag as any *"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".*

Voltage sags are characterised by their duration and depth. Duration is the length of time for which the voltage remains below a threshold. The concept of depth is somewhat a misnomer as a sag is characterised by the retained voltage, that is the voltage which persists during the sag, as opposed to the voltage decrease or 'lost' voltage. While the IEC definition does not give a set of definitive durations or level of retained voltage that must be observed for a disturbance to be classified as a voltage sag, IEEE Std 1159 [2] defines a voltage sag as a variation in the rms voltage of duration greater than ½ a cycle and less than 1 minute with a retained voltage of between 10 % and 90 % of nominal. This is the generally accepted definition of a voltage sag. Any disturbance that persists for less than ½ cycle is considered transient phenomena while voltage variations or disturbances of duration greater than 1 minute with retained voltages of less than 90 % of nominal may be considered as either sustained undervoltages or interruptions. Voltage sags are caused by large currents interacting with network impedances. The two main causes of voltage sags are network faults and the starting of equipment which draw large currents, particularly direct-on-line motors.

2.2. Measurement & Characterisation of Voltage Sags

Voltage sags are measured using specialised power quality monitoring instrumentation. The instrumentation must be configured with a sag threshold voltage. That is, a voltage level that will trigger a sag capture when the rms voltage falls below it. Voltage sags are characterised by reporting the duration for which the voltage variation persisted below the sag threshold combined with the maximum reduction in rms voltage, also known as depth. The depth is reported as the retained voltage. Figure 1 shows a graphical representation of a voltage sag including the sag threshold and the parameters (duration, retained voltage) used to report the sag. Note the

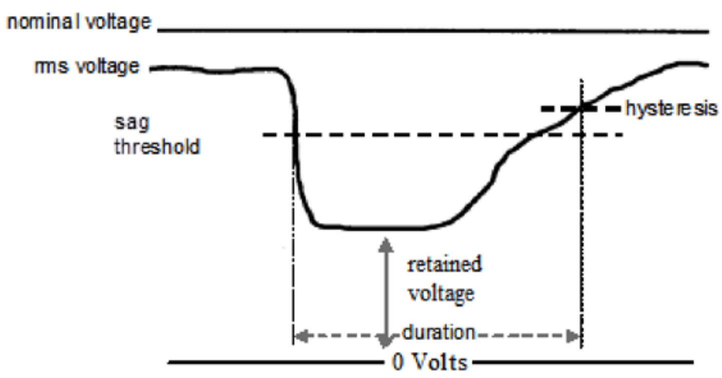

Figure 1: Example of a Voltage Sag

use of a hysteresis value in Figure 1; this value is used to prevent voltage levels which are close to the sag threshold crossing the threshold multiple times and triggering multiple sags which are basically due to the same event.

The theory of measurement, characterisation and reporting of voltage sags is considerably more complex than the basic overview given in this technical note. A detailed examination of this topic is beyond the scope of this technical note and readers are referred to [3] and [4] for further information.

3. Impact & Cost of Voltage Sags

There is a strong argument that can be made to claim that voltage sags are the most costly of all power quality disturbances. While perhaps not as costly as interruptions, voltage sags are much more prevalent and in some cases may have the same impact as a supply interruption. Relatively shallow voltage sags can lead to the disruption of manufacturing processes due to equipment being unable to operate correctly at the reduced voltage levels. Industrial equipment such as variable speed drives and some control systems are particularly sensitive to voltage sags. In many manufacturing processes, loss of only a few vital pieces of equipment may lead to a full shut down of production leading to significant financial losses. For some processes which are thermally sensitive a significant loss of material as well as the time taken to clean up and restart the process must also be considered.

There have been many studies which aim to quantify the cost of voltage sags. The results of these studies range from relatively modest cost associated with voltage sags through to very high costs generally at high technology industrial plants (such as semi-conductor manufacturing). Table 1 below reproduced from [5] show the costs associated with voltage sags from a range of industries.

Industry	Typical Financial Loss per Event (€)
Semiconductor Production	3 800 000
Financial Trading	6 000 000 per hour
Computer Centre	750 000
Telecommunications	30 000 per minute
Steel Works	350 000
Glass Industry	250 000

Table 1: Typical Financial Loss for Voltage Sags based on Industry [5]

Table 2 reproduced from [6] shows another summary of the impact of voltage sags on various industries from the US. The data presented agrees reasonably well with the data given in Table 1. It is stated in [6] that the cost to industry in the United States due to voltage disturbances is over $20 billion annually.

Industry	Loss per Voltage Sag ($US)
Paper Manufacturing	30 000
Chemical Industry	50 000
Automobile Industry	75 000
Equipment Manufacturing	100 000
Credit Card Processing	250 000
Semiconductor Industry	2 500 000

Table 2: Impact of Voltage Sags on Industry [6]

4. Characteristic of Voltage Sags in Australia

Data collected as part of the Long Term National Power Quality Survey (LTNPQS) project [7] has been used to develop characteristics of voltage sags in Australia. Using data collected from medium voltage sites (11 kV – 132 kV), Figure 2 shows a histogram of retained voltages while Figure 3 shows a histogram of voltage sag durations.

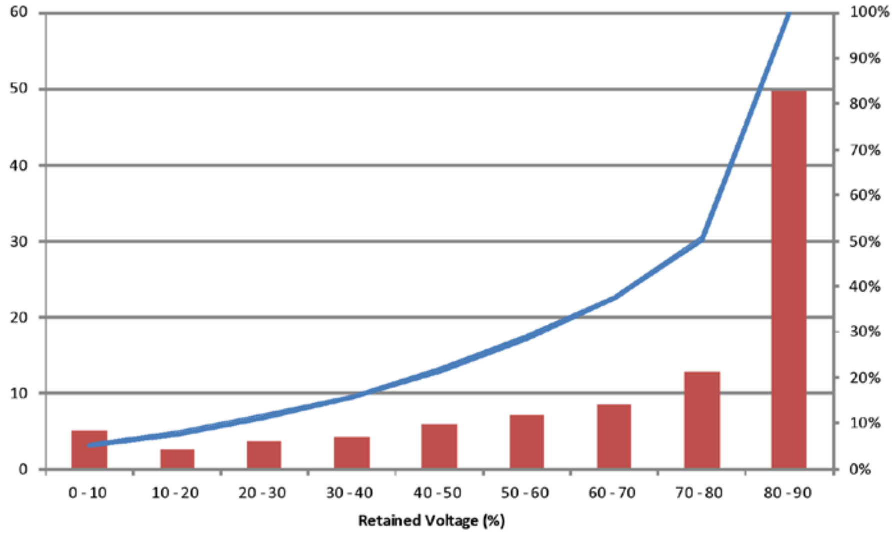

Figure 2: Histogram of Voltage Sag Retained Voltage

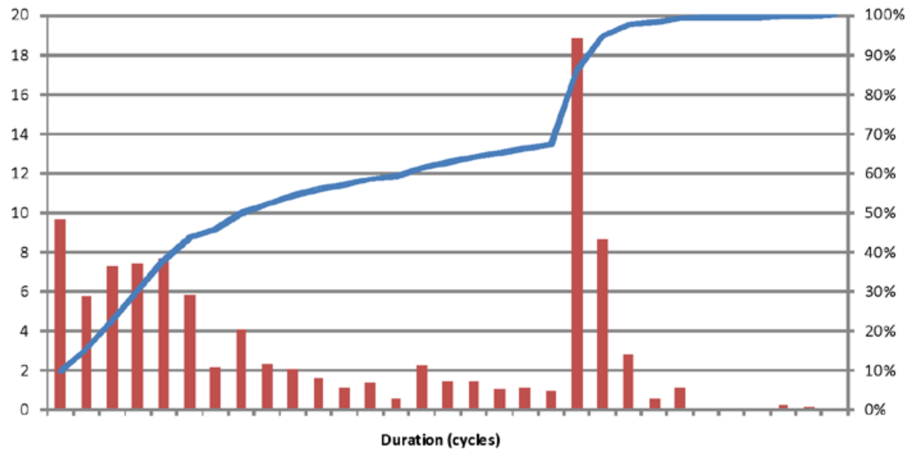

Figure 3: Histogram of Voltage Sag Duration

Using the data shown in Figure 2 and Figure 3 it is possible to develop voltage sag mitigation strategies based on a good understanding of the performance of the electricity distribution network. The data in Figure 2 shows that the vast majority of voltage sags have a retained voltage of greater than 80 %. In fact, 82 % of voltage sags are have retained voltage of 50 % or greater. This means that mitigation equipment capable of mitigating voltage sags with depth down to 50 % retained voltage will be effective in the vast majority of cases. Examination of sag durations, as shown in Figure 3, indicates that 68 % of voltage sags are of duration of 1 second or less. This figure gives an indication of the hold-up time required by mitigation devices if they are to be effective for most voltage sags. If the duration is extended to 2 seconds, 97 % of voltage sags fall within this duration.

5. Voltage Sag Mitigation Technologies

The large costs associated with voltage sags detailed in Section 3 can justify the use of sag mitigation strategies. This section of the technical note describes some of the most common methods of voltage sag mitigation including theory of operation as well as advantages and disadvantages.

5.1. Coil Hold-In Devices

Contactor coils are devices which have traditionally been susceptible to voltage sags. In some cases, the loss of a single contactor can lead to the loss of a whole production line even if all of the other equipment is immune to the voltage sag. A change to the contractor circuit or type can be a very simple and cost effective method of voltage sag mitigation. Coil hold-in devices are one such mitigation method. These devices are connected between the AC supply and the contactor and can generally allow a contactor to remain energised for voltage sags down to 25 % retained voltage.

5.2. Ferroresonant Transformer

A ferroresonant transformer, also known as a constant voltage transformer (CVT), is a transformer that operates in the saturation region of the transformer B-H curve. Voltage sags down to 30 % retained voltage can be mitigated through the use of ferroresonant transformers. Figure 4 shows a schematic of a ferroresonant transformer. The effect of operating the transformer in this region is that changes in input voltage only have a small impact on the output voltage (see Figure 5). Ferroresonant transformers are simple and relatively maintenance free devices which can be very effective for small loads. Ferroresonant transformers are available in sizes up to around 25 kVA. On the down side, the transformer introduces extra losses into the circuit and is highly inefficient when lightly loaded. In some cases they may also introduce distorted voltages. In addition, unless greatly oversized, ferroresonant transformers are generally not suitable for loads with high inrush currents such as direct-on-line motors.

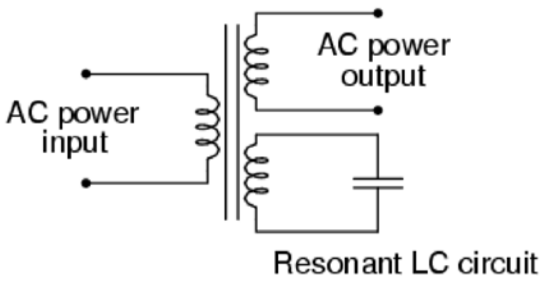

Figure 4: Schematic of a Ferroresonant Transformer [8]

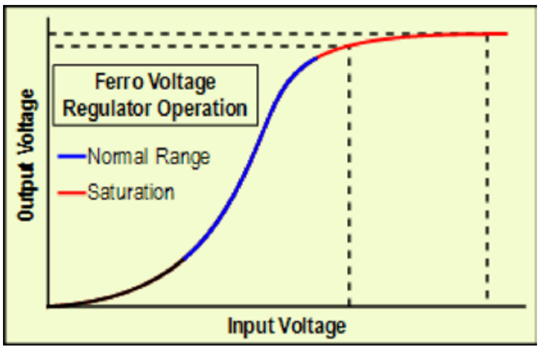

Figure 5: Ferroresonant Transformer Theory of Operation [9]

5.3. Uninterruptible Power Supply (UPS)

Uninterruptible power supplies (UPS) mitigate voltage sags by supplying the load using stored energy. Upon detection of a voltage sag, the load is transferred from the mains supply to the UPS. Obviously, the capacity of load that can be supplied is directly proportional to the amount of energy storage available. UPS systems have the advantage that they can mitigate all voltage sags including outages for significant periods of time (depending on the size of the UPS).

There are 2 topologies of UPS available; on-line and off-line. Figure 6 shows a schematic of an off-line UPS while Figure 7 shows a schematic of an on-line UPS. Comparison of the figures shows that the difference between the two systems is that for an on-line UPS the load is always supplied by the UPS, while for off-line systems, the load is transferred from the mains supply to the UPS by a static changeover switch upon detection of a voltage sag. The lack of a changeover switch renders the on-line system more reliable as any failure of the changeover switch will result in the off-line UPS being ineffective. UPS systems have disadvantages related to energy storage components (mostly batteries) which must be maintained and replaced periodically. Small UPS systems are relatively simple and cheap. However, large units are complex and highly expensive due to the need for large energy storage capacities.

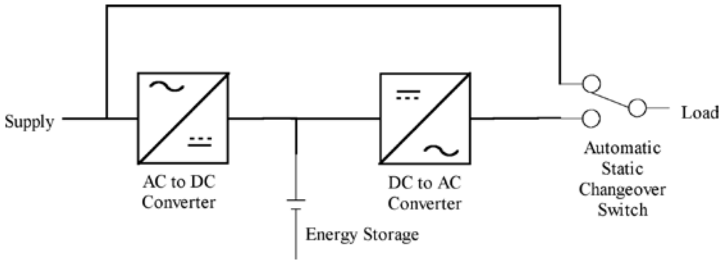

Figure 6: Block Diagram of an off-line UPS

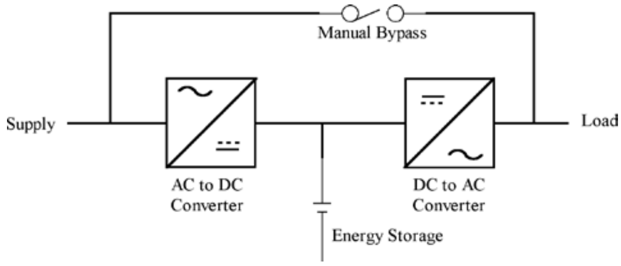

Figure 7: Block Diagram of an on-line UPS

5.4. Flywheel and Motor-Generator (MG)

Flywheel systems use the energy stored in the inertia of a rotating flywheel to mitigate voltage sags. In the most basic system, a flywheel is coupled in series with a motor and a generator which in turn is connected in series with the load. The flywheel is accelerated to a very high speed and when a voltage sag occurs, the rotational energy of the decelerating flywheel is utilised to supply the load. Flywheel storage systems are effective for mitigation of all voltage sags including interruptions and can supply the load for a significant period of time (up to several seconds depending on the size of the flywheel). Figure 8 shows the basic principle of the flywheel and motor-generator.

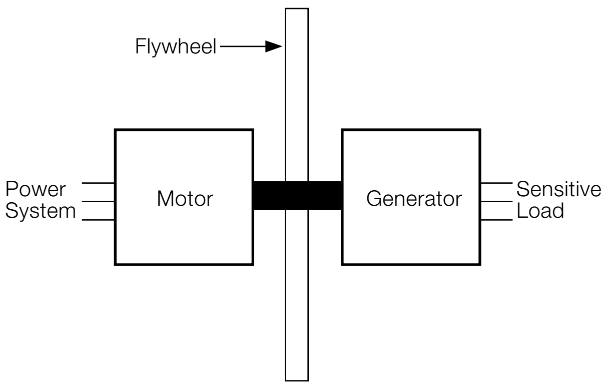

Figure 8: Basic Flywheel Motor-Generator Configuration [3]

Flywheels have maintenance and reliability advantages over other energy storage systems such as batteries. However, if large energy storage capacities are required, flywheels must be large and are heavy. Further, the configuration shown in Figure 8 will have high losses during normal operation [3]. A number of solutions have been proposed to overcome this issue and most involve the inclusion of power electronics into the system. Such a solution is presented in Figure 9. In this configuration, the motor which drives the flywheel is connected through a variable speed drive. This connection arrangement results in better starting characteristics for the flywheel and efficiency gains for the motor. Connection of the AC generator to a voltage source converter as shown increases the amount of energy that can be extracted from the flywheel due to the fact that the converter is able to produce a constant DC voltage, which may then be used directly or converted back to AC voltage, over a wide speed range.

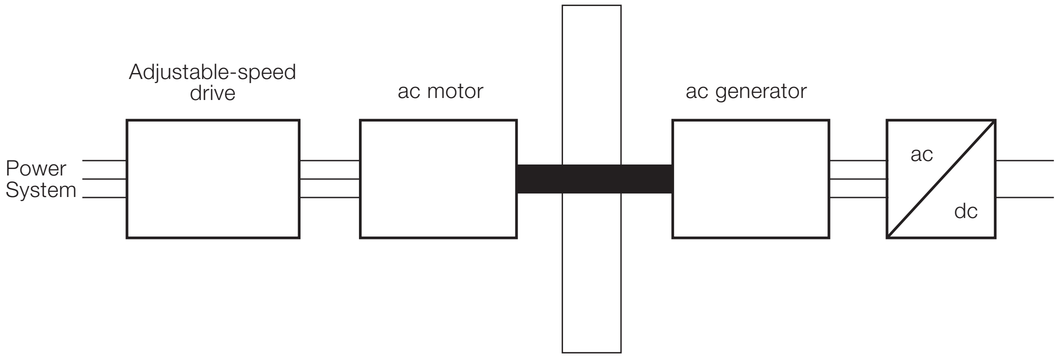

Figure 9: Impact of Sun Incidence Angle on Solar Cell Output [8]

5.5. Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restorers (DVR) are complicated static devices which work by adding the 'missing' voltage during a voltage sag. Basically this means that the device injects voltage into the system in order to bring the voltage back up to the level required by the load. Injection of voltage is achieved by a switching system coupled with a transformer which is connected in series with the load. There are two types of DVRs available; those with and without energy storage. Devices without energy storage are able to correct the voltage waveform by drawing additional current from the supply. Devices with energy storage use the stored energy to correct the voltage waveform. The difference between a DVR with storage and a UPS is that the DVR only supplies the part of the waveform that has been reduced due to the voltage sag, not the whole waveform. In addition, DVRs generally cannot operate during interruptions. Figure 10 shows a schematic of a DVR. As can be seen the basic DVR consists of an injection/booster transformer, a harmonic filter, a voltage source converter (VSC) and a control system. For readers who are interested in further knowledge of DVR systems, the article in [10] gives a thorough description of the design and operation of DVRs.

DVR systems have the advantage that they are highly efficient and fast acting. It is claimed in [10] that the DVR is the best economic solution for mitigating voltage sags based on its size and capabilities. In the case of systems without storage, none of the inherent issues with storage are relevant. Another advantage of DVR systems is that they can be used for purposes other than just voltage sag mitigation. These added features including harmonic mitigation, fault current limiting, power factor correction and reduction of transients.

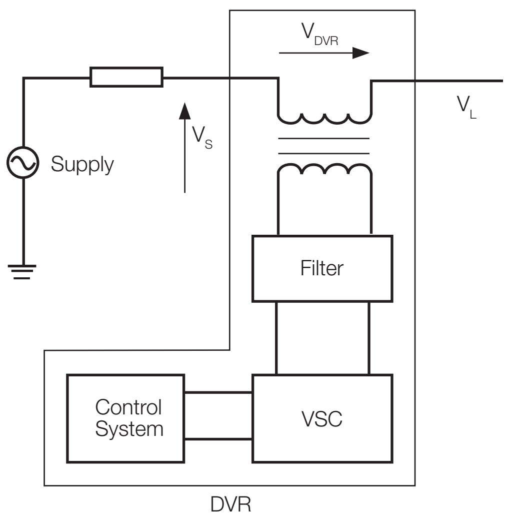

Figure 10: Block Diagram of a DVR [10]

5.6. Static Var Compensator (SVC)

A SVC is a shunt connected power electronics based device which works by injecting reactive current into the load, thereby supporting the voltage and mitigating the voltage sag. SVCs may or may not include energy storage, with those systems which include storage being capable of mitigating deeper and longer voltage sags. Figure 11 shows a block diagram of a SVC.

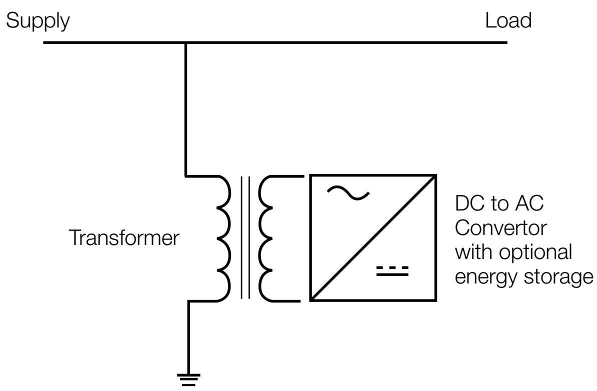

Figure 11: Block Diagram of a SVC

5.7. Sag Proofing Transformers

Sag proofing transformers, also known as voltage sag compensators, are basically a multi-winding transformer connected in series with the load. These devices use static switches to change the transformer turns ratio to compensate for the voltage sag. Sag proofing transformers are effective for voltage sags to approximately 40 % retained voltage. Figure 12 shows a block diagram of a sag proofing transformer.

Sag proofing transformers have the advantage of being basically maintenance free and do not have the problems associated with energy storage components. A disadvantage is that at this stage, sag proofing transformers are only available for relatively small loads of up to approximately 5 kVA. With the transformer connected in series, the system also adds to losses and any failure of the transformer will lead to an immediate loss of supply.

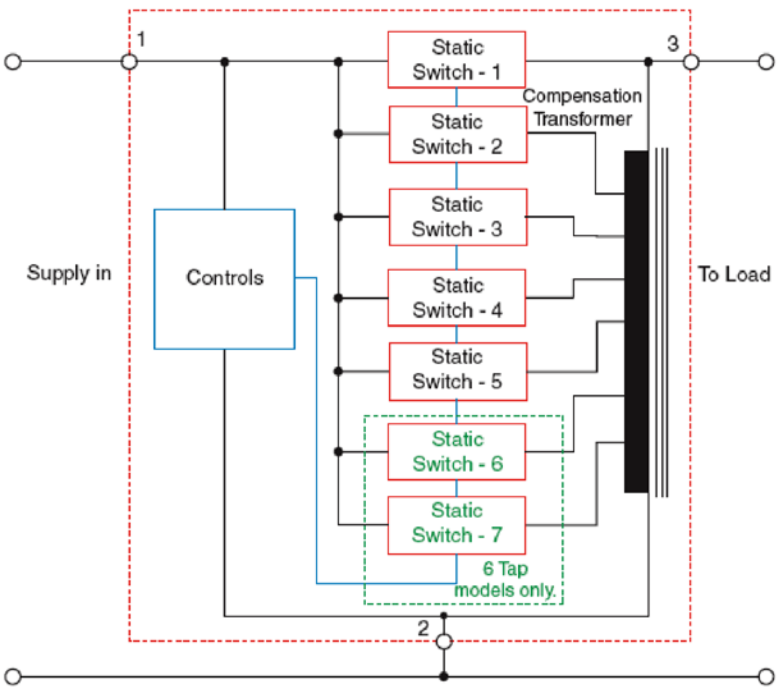

Figure 12: Block Diagram of a Sag Proofing Transformer [11]

5.8. Static Transfer Switch (STS)

For facilities with a dual supply, one possible method of voltage sag mitigation is through the use of a static transfer switch. Upon detection of a voltage sag, these devices can transfer the load from the normal supply feeder to the alternative supply feeder within half a cycle. The effectiveness of this switching operation is highly dependent on how independent of each other the 2 supply feeders are and the location of the event leading to the voltage sag. Ideally, with a dual feeder supply, the 2 feeders should be supplied by different substations. Obviously, there are significant costs associated with dual supplies even if they are available.

6. Energy Storage Technologies

Although not sag mitigations device by themselves, energy storage systems are essential to many of the above sag mitigation technologies. As such, a short description of energy storage technologies is relevant to this technical note. In cases of devices such as the DVR and SVC, the device is compatible for use with a number of different energy storage technologies. The choice of technology generally depends on the application, maintenance requirements and cost. At present there are four main energy storage technologies that may be applied to sag mitigation technologies. These are flywheel, batteries, superconducting magnetic energy storage (SMES) and capacitors.

6.1. Flywheels

Flywheel energy storage systems are one of the oldest storage technologies with examples dating back to the 11th century [12]. Modern flywheel systems incorporate advanced materials such as carbon fibre, have magnetic bearings and may spin in a vacuum to reduce losses.

Flywheels have the advantage that they are simple and low maintenance. They also have a long lifespan. Generally flywheels do not contain materials which are particularly dangerous to the environment. On the downside, they introduce losses into the system and may not charge as fast as other devices such as capacitors.

6.2. Batteries

Battery energy storage is another systems have been in existence for a considerable period of time. Although an area of continual research, battery technologies are well developed and well understood. Batteries are relatively cheap and when maintained correctly provide excellent performance. In addition, batteries have the highest energy density of all the considered energy storage technologies. The main disadvantage of batteries is that they have a finite number of charge cycles and hence a limited lifespan. They also contain materials which may be hazardous to the environment.

6.3. Capacitors

Capacitors and the modern super or ultra-capacitors are becoming a more popular choice for energy storage. Capacitors are simple and have very fast charge times. They do not have the charge cycle limitations of batteries and hence may have a longer lifespan if not subject to overvoltage stress. Cost for capacitors varies on the application but is higher than the cost of batteries. Disadvantages of capacitors include relatively higher costs compared to batteries and relatively lower energy density levels compared to batteries.

6.4. Superconducting Magnetic Energy Storage (SMES)

SMES systems are a developing technology which utilise the properties of superconducting material to store energy in magnetic fields. SMES systems have very fast charge and discharge times which make them an attractive energy storage system for sag mitigation. Another advantage of SMES systems is the very low losses due to the superconducting characteristics. The main disadvantage of SMES over batteries at present is the cost. SMES systems also have all of the disadvantages associated with superconducting technology, not least of which is the need for liquid nitrogen to maintain the cryogenic temperatures required for superconductivity.

7. Cost of Sag Mitigation Technologies

7.1. Cost of Mitigation Technologies

This section of the technical note attempts to quantify and compare the costs of the various mitigation devices discussed above. For all technologies, there will be two costs involved. The first is the initial purchase price of the equipment while the second is the maintenance costs associated with the selected equipment. There are a number of studies which give the costs of mitigation technologies and not all agree well with each other. Table 3 shows a range of costs for a number of the mitigation technologies discussed above. It can be seen that the DVR is the cheapest mitigation technology on a cost per kVA basis. However, DVR systems are usually only used for large loads and the costing is based on this fact. UPS systems or ferroresonant transformers are the only viable mitigation strategies for small load.

Mitigation Technology	Initial Cost ($)	Operation Cost (% of Initial Cost per Year)
Coil Hold-In Devices	100 – 150 each [13]	N/A
Ferroresonant Transformer (CVT)	1000/kVA [14]	1 [14]
UPS	500/kVA [14] - 1000/KVA [13]	1.5 - 2.5 [14] 10 [15]
Flywheel	500/kVA [14]	0.7 [14]
DVR (50 % voltage boost)	250/kVA [14]	0.5 [14]
Statcom	400/kVA [15]	5 [15]
Static Switch (10 MVA)	600 000 [14]	0.5 [14]

Table 3: Cost of Voltage Sag Mitigation Technologies

7.2. Comparison of Costs of Storage Technologies

Table 4 on the following page, reproduced from [3], gives a comparison of the cost of energy storage technologies depending on the application. It can be seen that for all applications, battery energy storage systems (BESS) remain the cheapest solution while, depending on the application, capacitors or superconducting magnetic energy storage (SMES) may be the next cheapest.

Power	Ride-through Time	Costs of Energy Storage ($)		
		SMES	BESS	Capacitors
300 kW	1 s	183 000	6300	56 000
	60 s	389 000	6300	3 350 000
3 MW	1 s	411 000	63 000	558 000
	60 s	1 064 000	63 000	33 500 000

Table 4: Cost of Storage Technologies

8. Conclusion

This technical note described voltage sags including their characteristics, causes, measurement and financial impact. A number of techniques which may be utilised to mitigate voltage sags have been described along with the advantages and disadvantages of each. Finally a comparison of the costs of each voltage sag mitigation technology has been given.

9. References

[1] IEC60050-604, International Electrotechnical Vocabulary. Chapter 604: Generation, transmission and distribution of electricity - Operation, IEC, 1998.

[2] IEEE Std 1159-2009, IEEE Recommended Practice for Monitoring Power Quality, IEEE, 2009.

[3] Math H. J. Bollen, Understanding Power Quality Problems - Voltage Sags and Interruptions, 2000, New Jersey, John Wiley & Sons.

[4] V.J. Gosbell, D. Robinson, S. Perera, The Analysis of Utility Voltage Sag Data, International Power Quality Conference, Singapore, October 2002.

[5] David Chapman, Power Quality Application Guide - The Cost of Poor Power Quality, Copper Development Association, 2001.

[6] B. H. Chowdhury, Power Quality, in IEEE Potentials, Vol 20, No 2, 2001.

[7] S. Elphick, V. Gosbell, V. Smith, R. Barr, The Australian Long Term Power Quality Survey Project Update, 14th International Conference on Harmonics and Quality of Power, ICHQP'10, Bergamo, Italy, 26 - 29 September 2010.

[8] All About Circuits, Voltage Regulation, Available from: http://www.allaboutcircuits.com/vol_2/chpt_9/6.html, Last Accessed 3rd February 2012.

[9] The Automatic Voltage Regulator – AVR: Guide and Comparison, Available from: http://www.ustpower.com/Support/Voltage_Regulator_Comparison/Ferroresonant_Transformer_CVT/Constant_Voltage_Transformer_Operation.aspx, Last Accessed 3rd February 2012.

[10] Chellali Benachaiba, Brahim Ferdi, Voltage Quality Improvement Using DVR, Electrical Power Quality and Utilisation Journal, Vol. XIV, No. 1, 2008, p. 39 - 45.

[11] Sag Proofing Technologies Inc, Installation and Service Manual - Voltage-Sag Compensators, 2005.

[12] Wikipedia, Flywheel, Available from: http://en.wikipedia.org/wiki/Flywheel#History, Last Accessed 8th February 2012.

[13] Pacific Gas and Electric Company, Voltage Sag Ride-Through Mitigation in Sequence by Increasing Cost, 1999.

[14] Tosak Thasanutariya, Somchai Chatratana, Mark McGranaghan, Economic Evaluation of Solution Alternatives for Voltage Sags and Momentary Interruptions, in Electrical Power Quality and Utilisation Magazine, Vol 1, No 2, 2005.

[15] M. Didden, R. Belmans, W. D'Haeseleer, Cost-Benefit Analysis of Voltage Sag Mitigation Methods in Fiber Extrusion Plants, in ETEP, Vol 13, No 2, 2003.

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APQRC

Endeavour Energy

UNIVERSITY OF WOLLONGONG AUSTRALIA

For more information please contact:

Sean Elphick
Australian Power Quality and Reliability Centre
University of Wollongong
Northfields Avenue
Wollongong NSW 2522
Australia

Phone: +61 2 42214737
Fax: +61 2 42213236

Email: elpho@uow.edu.au
Web: www.elec.uow.edu.au/apqrc