

A review of voltage dip mitigation techniques with distributed generation in electricity networks

O. Ipinnimo^{a,*}, S. Chowdhury^a, S.P. Chowdhury^a, J. Mitra^b

^a Electrical Engineering Department, University of Cape Town, South Africa

^b Electrical & Computer Engineering Department, Michigan State University, East Lansing, MI, United States

ARTICLE INFO

Article history:

Received 24 October 2012

Received in revised form 23 April 2013

Accepted 6 May 2013

Keywords:

Artificial neural network

Distributed generation

Power quality

Reactive power

Root mean square

Voltage dip

ABSTRACT

The advent of power quality sensitive equipment has made the provision of good power quality a real challenge across the globe. With the increasing usage of sophisticated sensitive electronic equipment in industrial, residential and commercial sectors, it is important to protect them from any power quality disturbance in order to avoid equipment damage and malfunction leading to financial loss for the customer. Voltage quality disturbances such as voltage dips pose a serious concern as a power quality problem, since due to their stochastic nature they cannot readily be eliminated from regular utility systems. However, they can be mitigated. High degree of penetration of distributed generation in power networks is useful in delivering different benefits to the utility in the form of ancillary services one of which is voltage dip mitigation in case of system contingencies. This paper presents a comprehensive review and comparison of various distributed generation schemes used by utilities for mitigation of voltage dips in power networks.

1. Introduction

Increased utilization of renewable energy resources together with a drive for power sector deregulation and restructuring is leading to the growth in the development and deployment of renewable and low-carbon distributed generation (DG) [1]. In the United Kingdom, there is a set goal to raise the generation of electricity from renewable resources up to 15% in 2020, and the United States (US) has planned that 22% of new installed generation capacity should come from DG by 2020 [2]. In Japan, the projection of the electricity substitution by renewable energy in 2050 is for 10% of wind power, 18% of solar energy, 14% of biomass, 10% for geothermal heat and 14% for hydraulic power [3].

Existing research literature reflects that DG is spreading rapidly in most networks due to the need for reducing environmental pollution and global warming caused by emission of carbon particles and greenhouse gases [4]. Furthermore, in many developing countries, the lack of infrastructural resources to construct new centralized power generating stations and the opportunity to quickly deploy modular DG has also contributed to increased penetration of DG. It is estimated [5] that within the next two or three years, DGs may represent up to 30% of all new generation.

recent liberalization of the energy industry in many parts of the world has led to open competition among power utilities. This has led to electricity being provided at higher reliability and quality than ever before [6]. The increased use of ICT (information communication technology) and semiconductor devices (switched mode power supplies) at home and offices have also led to monitoring of voltage profile and increased the challenges for utility and industry to focus on power quality. In a healthy power network, the power generated must be equal to the load demand at any particular point of time. Any reactive power imbalance in the system disturbs the voltage at the load points and the voltage profiles along the network. The IEEE Std. 1159-1995 definitions to label root mean square (r.m.s) voltage disturbances are based upon its duration and voltage magnitude. Short duration r.m.s variations are divided into the instantaneous, momentary, and temporary time periods, while the voltage magnitude of the disturbance characterizes it as a dip, swell, or interruption. A long-duration r.m.s voltage variation is defined to last longer than one minute, and can be classified as a sustained interruption, under voltage, or over voltage depending upon its magnitude [7]. This is shown in Fig. 1.

In some literature [8] voltage dip is regarded as complete loss or a short term reduction in the r.m.s voltage and is always expressed in terms of the retained voltage and duration. It also means that the necessary reactive power is not being transferred to the load. In past decades, several attempts were made to improve the voltage profile by placing distributed reactive power sources such as capacitor banks for optimal sizes at optimal locations on the network [9]

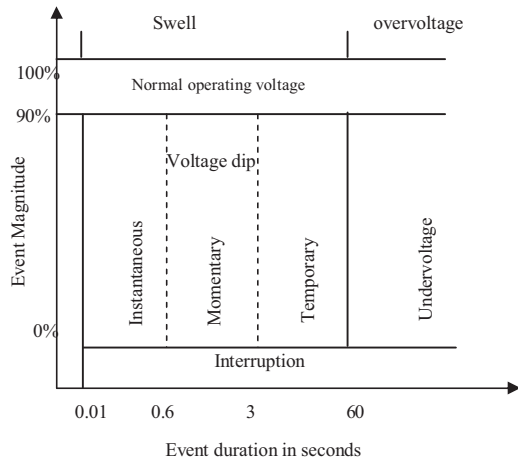


Fig. 1. Definition of voltage dips according to IEEE Std. 1159-1995 [8].

2. Impact of distributed generation on power quality

2.1. Distributed generation (DG)

DG is still a relatively new method of electrical power generation today, and different terms have been used to describe and explain DG. In general, it is usually referred to as an electric power source connected directly to the distribution system (either the medium voltage or low voltage) or on the industrial facility grid at the customer site of the meter. They include photovoltaic (PV), wind, fuel cells, microturbines, and reciprocating internal combustion engines with generators. DGs are likely to have different impacts on a power system operation depending on their application, location, rating, nature of consumers, technology, environmental impact, mode of operation, ownership and degree of penetration [10]. Therefore, deployment and utilization of DG for maximum benefit require detailed evaluation of the technical impacts of DG penetration on system reliability, power flow, voltage profile and stability, protection coordination and quality of power supplied to the customers.

The assessment of PQ (power quality) levels is important in a power network before and after the installation of DG as the DG might have an inadvertent negative impact on the PQ of the network. The impact of DG on PQ depends on its connection to the network which can either be direct or through a power-electronic interface.

When connected directly to the distribution system, it influences the background waveform distortions, modifies the harmonic impedances and contributes to modification of voltage harmonic profiles at all of the distribution system buses. Connection through the power electronic interface can inject harmonic currents, which can lead to a voltage distortion increase [11].

However, if properly integrated, DGs can benefit the utility network in many ways by providing several ancillary services such as reactive power and voltage control, supply of reserves, voltage regulation and stability [12].

DG can also provide additional services like voltage quality (VQ) disturbance compensation such as voltage dip mitigation [13], which lead to the improvement of PQ and alleviate PQ disturbances. Placing a DG unit on the distribution feeders helps mitigate the voltage dips experienced by the load connected to the feeder terminals. The optimal placement and sizing of DG help in loss reduction, voltage profile improvement and voltage dip mitigation, which might lead to undistorted power at the PCC. Loss reduction is important in electricity generation and distribution for as it directly increases utility profit in a competitive electricity market [14]. In order to

secure quality power supply various solutions have been proposed by several researchers. With more renewable DG penetration into the network, utilizing the DGs for improving power quality through voltage dip mitigation has become an important area of research in itself. This has led to the development of various distributed generation schemes for the mitigation of voltage dips in electricity networks.

2.2. The technical limitations and shortcomings of DG

When a large number of DG units are connected to the distribution side of a power network, it will seriously affect the distribution system design, control, operation, protection, as well as reliability and security of the system. This requires planning method and making appropriate changes to the traditional distribution network [15]. In spite of the growing number of DG units in both medium and low voltage networks, their contribution of power delivered to the utility grid remains small, as compared to the power injected by centralized power plants. In most cases the availability of renewable energy, such as sun, water and wind determines the feasibility of a renewable energy system. Generally power flows are unidirectional from higher to lower voltage levels (from transmission to distribution) but with the presence of DG units in the medium-voltage or low-voltage grid, the power flows will be bidirectional in the affected feeders. This may have negative impacts on power quality, such as voltage regulation, frequency deviation, harmonic distortion, islanding and conflicts with relaying and reclosing. Research literature indicates the following a shortcomings of DG schemes as listed below.

- (1) Change in voltage profile along the distribution network.
- (2) Increase in short circuit level (in grid-connected mode).
- (3) Voltage transients as a result of connection, disconnection and the operation of the DG.
- (4) Congestion in the system, thereby affecting power quality and reliability.
- (5) Overloading of lines and equipment leading to thermal overloading.

2.3. The economic limitations and shortcomings of DG

For safe operation and protection to be guaranteed at all times in a DG connected distribution network, with bidirectional power flow. Different protection schemes may be required. This will ensure optimize reliability and availability of supplied power since fault current not only comes from the main power system but also from the DG units. This makes detection far more complicated and requires more cost. Power networks with DG units have a higher maintenance costs when compare with power networks without DG units. Its maintenance requires maintaining multiple generators in multiple locations. The stochastic and unpredictable nature of renewable energy also means a higher cost for balancing the electricity grid and maintaining reserve capacity.

3. Definition of voltage dip phenomena

3.1. Definition and causes of voltage dips

Voltage dip is defined as a sudden reduction of the supply voltage at the power frequency to a value between the ranges of 10% to 90% of nominal voltage followed by a voltage recovery after a short duration usually from 10 ms up to 60 s [16]. An example of a typical voltage dip is shown in Fig. 2. It commences when the declared voltage drops to a lower voltage than the threshold voltage V_{thr} (0.9 p.u. or 90%.) at time T1, it continues up to T2 at which the voltage

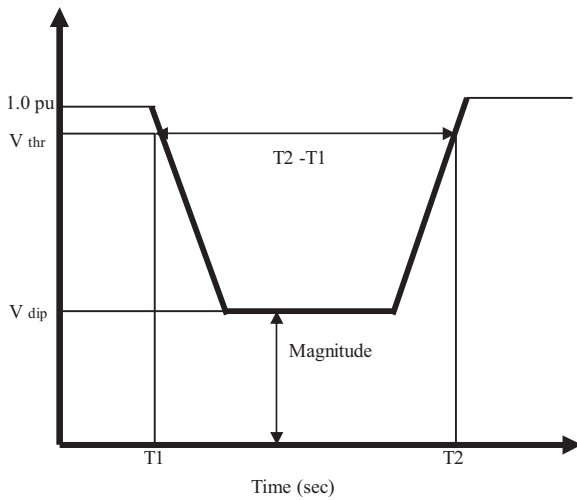


Fig. 2. Voltage dip [17].

recovers to a value over the threshold value. The magnitude of the voltage dip is V_{dip} and its duration is $T2 - T1$ [17]. The causes of voltage dip can be categorized into man-made and natural. Man-made causes (due to human activities on the power network) include switching operations or starting of large motors, power system faults (short circuit), power swings, sudden load changes, generating stations coming on/off line, unplanned load growth and indiscriminate integration of distributed generation. The natural causes include regulator dysfunction, bad weather, pollution, animals and birds, etc.

3.2. Impacts of voltage dip on consumers

Impact of voltage dip on power system and electrical equipment depends on its severity in terms of magnitude and duration. The process industry equipment and industrial induction motors, especially those in the textile industry or refineries are particularly susceptible to voltage dips because the motors are joined with one another and also with other electrical components in the system. If any of the component in the system is affected by voltage dip and it trip. The entire process is affected, and this can cause the whole plant to shut down. In industries and process control, computers and other PQ sensitive control and instruments are widely used, and these are particularly sensitive to voltage dips. Following a shutdown, the time to restart the industrial processes and production might take hours even days. This results in production and hence financial losses to the organization.

It is important to be specific when talking about the dip magnitude or depth. It can be the voltage drop (missing voltage) or the remaining (retained) voltage. The work described here will emphasize only on the retained voltage as voltage dip magnitude or depth. The dip duration and depth experienced by a customer depends on network topology, distance to fault location and fault clearing device set up in the grid [18]. Customers, miles away from the fault location, can still experience a voltage dip resulting in equipment mal-operation when the fault is on the transmission system.

Voltage dip also affects the lighting loads of residential and commercial consumers. The contribution of lighting loads like the incandescent lamps, fluorescent lamps, compact fluorescent lamps (CFLs) and solid state LED lights, to the total electric power demand is around 20% of the world electricity consumption [19]. Fluorescent lamps and CFLs, being discharged lamps, need a high voltage to initiate discharge during starting, and hence are more susceptible to voltage dips. Other effects include mal-operation of data

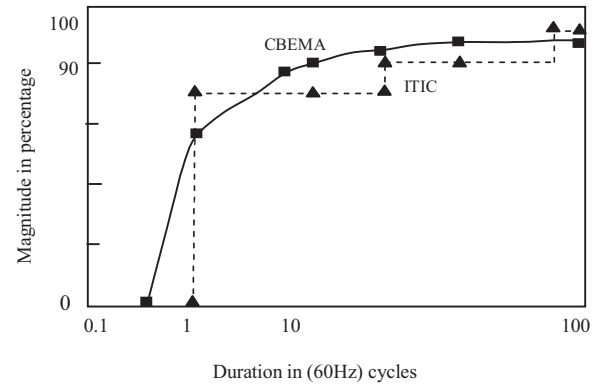


Fig. 3. Voltage tolerance requirements for computing equipment [8].

processing equipment, which can suffer from data loss and malfunctioning of sophisticated and sensitive electronic equipment.

3.3. Voltage standards in engineering practices

Various engineering bodies and grid codes of many countries specify as standards, the voltage and frequency requirements for electrical equipments. The manufacturers of electrical appliances and power utilities comply with these standards while providing their products/services to their customers. Widely used standards dealing with power quality come from the IEEE, IEC, CBEMA and SEMI [6].

During electrical installation, many sensitive devices are connected. Those devices might have different sensitivities toward voltage dips and can be distinguished by their individual voltage-tolerance performance curve. The most widely used voltage-tolerance curves are the CBEMA (Computer Business Equipment Manufacturers Association) curve and the ITIC (Information Technology Industry Council) curve. Fig. 3 shows the well-known Computer Business Equipment Manufacturers Association (CBEMA) curve. The curve sets a reference for equipment voltage tolerance as well as for the severity of voltage dips [20].

4. Voltage dip mitigation

Various methods and solutions have been proposed by power and energy researchers to alleviate voltage dip and other PQ disturbances. In the literature, methods of voltage dip mitigation have been classified into active and passive measures. The active measures are used to reduce the number of voltage dips acting on the causes that generate the disturbances such as reducing the number of faults. On the contrary, the passive ones are protection measures that try to compensate for the voltage reduction during the disturbance [21]. Ongoing research works have demonstrated the utilization of DG for improving the power quality, especially for mitigating voltage dip problems [22]. Several methods or schemes have been reported and proposed with DG.

To reduce the number of sustained blackouts or dip has always been one of the main goals in the planning and operation of any power network. If there are fewer faults occurring in a power system, there will be fewer voltage dips caused by faults [8]. Some of the active measures taken to reduce voltage dips include implementing a strict policy for maintenance and the use of surge arresters instead of spark gaps.

The passive measures involve compensating for the missing voltage during the dip. The work of Martinez-Velasco et al. [22], and some other researchers have shown how to utilize DG to mitigate the problem of voltage dips in an electrical power system. Besides the DG schemes, consumers might use their own equipment for

solving the problem of voltage dips at their premises. At a very low voltage, voltage dip mitigation equipment such as the voltage stabilizer can be used to deal with voltage dip. In this case no energy storage mechanism is required. The automatic voltage stabilizers rely on generating full voltage from the available energy supply at reduced voltage during the dip. The main types of automatic voltage stabilizers are electro-mechanical, ferro-resonant or constant voltage transformer (CVT), electronic step regulators, etc. [23].

4.1. DG schemes for voltage dip mitigation

Load variation or fault can cause a voltage dip; many times voltage dip is a function of the reactive component of the load current, system and transformer resistance. In electrical power system, reactive power is either generated or consumed in almost every component of the system. This affects the voltage profile on the power system. DG has made it economical to supply this reactive power closer to the load and also improve the voltage profile in the distribution system [24]. There have been various DG-based schemes for voltage dip mitigation, which include the following.

4.1.1. Application of converter-based DG, synchronous and asynchronous generators

Voltage dip can be controlled by three types of DG units viz., asynchronous generators, synchronous generators and converter-connected units. The presence of synchronous and power electronics equipped induction generators has a positive effect on the retained voltage during voltage dips. Here the machines inject reactive power into the grid as a result of voltage dip and this surely increases the retained voltage during the dip. The behavior of converter-based DG, synchronous generators, and asynchronous generators during voltage dips is verified and analyzed by [25]. In opposition to the reported effects of synchronous and asynchronous generators on voltage dips in high to medium voltage networks, their influence on voltage dips in low voltage networks is rather minimal. Converter-based DG is found to have a similar effect on voltage dips in low voltage networks, in opposition to high-voltage networks.

The voltage divider model was used to study the effect of DG units on voltage dip. The analysis is based on voltage dips caused by short circuits fault has shown in Fig. 4. The model consists of source impedance Z_s at the point of common coupling (PCC) and the impedance between PCC and the fault Z_f . In this model all loads are initially supposed to be of the constant impedance type. This allows including contribution of the loads into the source impedance. The voltage V_{pcc} at the PCC is thus given by (1) which is the dip magnitude at the PCC.

$$V_{pcc} = E_s \frac{Z_f}{Z_s + Z_f} \quad (1)$$

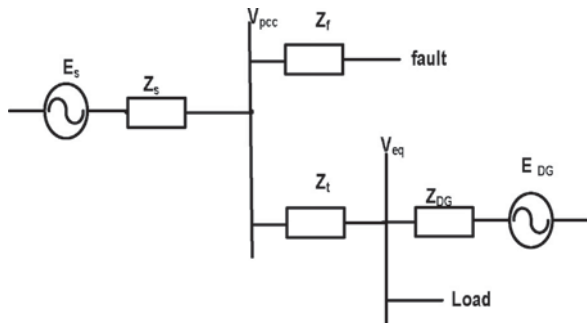


Fig. 4. Voltage divider model [25].

If another branch is added to the PCC with impedance Z_t which is the impedance between the PCC and the equipment terminals, this impedance can also include transformation to lower voltage levels. The voltage at the equipment terminals V_{eq} will be strongly dependent on the behavior of the connected DG units, represented in the scheme by a voltage source E_{DG} and impedance Z_{DG} . The voltage at the equipment terminals is given by (2)

$$V_{eq} = V_{pcc} \frac{Z_{DG}}{Z_t + Z_{DG}} + E_{DG} \frac{Z_t}{Z_t + Z_{DG}} \quad (2)$$

The advantage of a converter-connected DG, on a low-voltage distribution feeder which was simulated for seven different types of voltage dips with the three types of DG connected to the distribution feeder. The voltage dips as experienced by the load connected to the equipment terminals were mitigated most by converter-connected DG. However, the improvements are small as compare to the effects of DG on voltage dips in high-voltage networks.

Ramesh et al. [26], analyze the effects of different DG units for various fault conditions on voltage dip using IEEE 13 bus system. This investigation shows that synchronous generator improves the voltage profile as compare with the induction generator. This is due to its reactance power absorbed during recovery process. The work of Ipinnimo et al. [27] simulate the schemes with three types of wind turbine generators (WTGs), the squirrel cage induction wind turbine generator (SCIWTG), double-fed induction wind turbine generator (DFIWTG) and synchronous wind turbine generator (SWTG) for mitigation of multiple voltage dips within a short period of time in a medium voltage distribution network. It was found that the three WTGs have different impact despite that they have the same power rating. SWTG have the highest voltage magnitude during mitigation, SCIWTG and DFIWTG have no automatic voltage regulation and hence no reactive power regulation capability. Therefore, medium-voltage distribution feeder to which these generators are connected needs to supply all the reactive power necessary during the voltage dips. These generators create a reactive power burden for the power network and may degrade system performance rather than support it.

The results given by [28] shows that area of vulnerability (AOV), voltage dip frequency and voltage dip index are improved when DG is installed in a distribution system. The impact of DG on voltage dip assessment depends on characteristics of DG such as the size of DG and location. The size of DG has no significant impact on AOV and dip frequency when DG operates in the voltage control mode. When the DG operates in the power factor control mode, the size of DG has influence on AOV and dip frequency by decreasing them slightly. The location of DG can also have impact on mitigating voltage dip severity. If DG is installed at the same feeder or very close to the fault, the performance of dip mitigation is high. However, when installed at a different feeder the performance of dip mitigation is lower, but it is still better than without DG installed in the system.

4.1.2. Series compensation

Macken et al. [29] proposes a solution to the problem of voltage dip in transmission networks with the introduction of either a shunt current or a series voltage into the system and during this process distributed generation systems play an important role. The introduction of a shunt current or a series voltage to the system makes the mitigation of voltage dips possible on the grid. This can also be done using a power electronic converter of a distributed generation system, which involves a high active current if the voltage has to be restored in both magnitude and phase angle to its pre-fault values. The power electronic converter of a distributed generation system can be extended with a series compensator as shown in Fig. 5.

Dynamic voltage restorer (DVR) can also be used in series compensation to mitigate voltage dip with distributed generation based

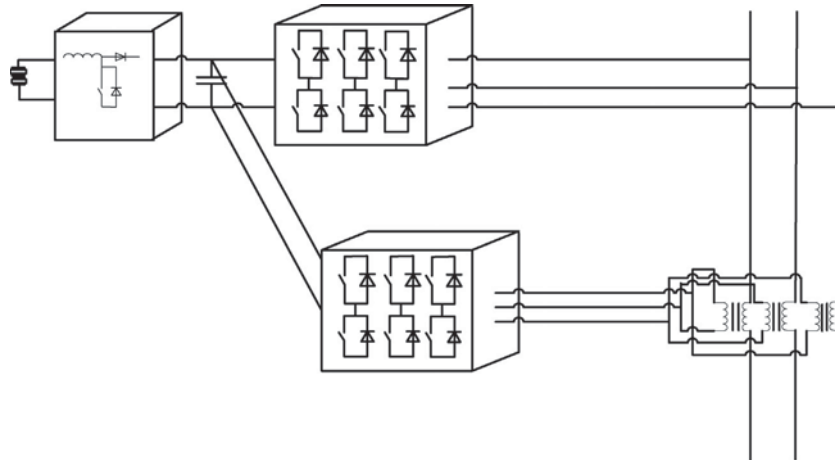


Fig. 5. A grid-interfaced distributed generation system extended with a series compensator [29].

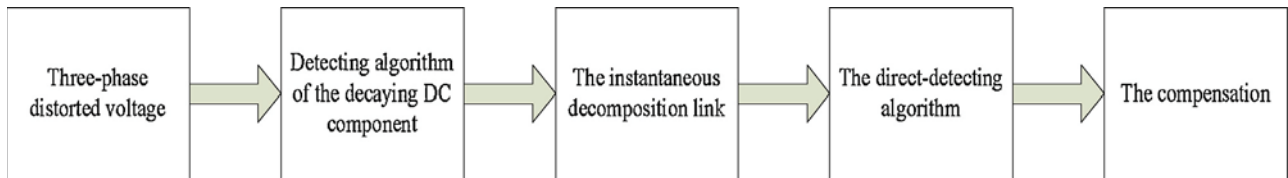


Fig. 6. Flow diagram of voltage compensation detection method [31].

on symmetrical component estimation. This method ensures the correction of the positive sequence amplitude during dip to the sensitive loads [30]. A DVR is a power-electronics-converter based device that has been designed to protect critical loads from many kinds of disturbances. It is connected in series with a distribution feeder and is capable of generating or absorbing real and reactive power at its AC terminals. The DVR consists of a voltage source inverter, a switching control scheme, a DC energy storage device that may be supplied by DG, output filter and an injection or coupling transformer is connected in series with the AC system. The operation of a DVR is to insert a voltage of required magnitude, the DVR can restore the sensitive load voltage to the desired amplitude and waveform. Liu et al. [31] shown how this can be achieved. The main function of the DVR is to inject appropriate voltage components along the distribution feeder to balance the line currents. The detection process of the voltage compensation is shown in Fig. 6.

Series compensation is very effective for mitigating voltage dips and can also be used to control the voltage in the event of other disturbances. By using appropriate control algorithms and sufficiently fast switching, the series compensator may be able to mitigate voltage transients, excessive voltage harmonics, and voltage fluctuations leading to light flicker.

It has the following disadvantages:

- (1) It cannot be used during voltage dips that exceed the rating of the series converter.
- (2) It requires more power electronic components.

4.1.3. Transfer to microgrid operation during dips

In this scheme, the DG unit has to be designed for both grid-connected operation and microgrid (islanded) operation. During grid-connected operation, the converter controller of the DG system regulates the current (i.e. current-mode control), whereas in microgrid operation, the controller regulates the voltage (i.e. voltage-mode control).

The DG system, which is connected through a power electronic converter to the grid, a three-phase static transfer switch is inserted

between the utility supply side and the load side. When a voltage dip occurs, the static transfer switch is opened to disconnect the load side, where sensitive equipment is located, from the utility supply side. The static transfer switch comprises back-to-back thyristors. The DG system at the load side regulates the voltage during the time that the loads are isolated from the utility supply. In this way, the operation of sensitive equipment is not affected by the voltage dips, assuming that the transfer between grid-connected operation and microgrid operation is seamless. During microgrid operation, the DG supplies all the power needed by the loads [29]. In this way, the operation of sensitive equipment is not affected by the voltage dips. Fig. 7 shows a grid interfaced DG system which is isolated from the utility supply during dips by a static transfer switch.

Microgrid operation has several advantages such as it can be used during voltage dips and interruptions and is also a cheaper solution as the amount of power electronic component is clearly less [32]. However, its operation during the voltage dip is not as much reliable than the series compensator.

4.1.4. Shunt active filter with energy storage (SAFES)

voltage dip mitigation using DG in a microgrid can also be done with a shunt active filter with energy storage [33]. The proposed control strategy is based on the state space pole placement design for a shunt active filter with energy storage installed in a microgrid which guarantee voltage regulation and harmonic cancellation at the load site. During voltage dip, the reference fundamental current for the SAFES is calculated and it works in conjunction with local distributed generation to control the voltage at the point of common connection (PCC).

The application of SAFES helps the voltage and power improvement within a microgrid in presence of distributed generation. Theoretical analysis has investigated shown how to control a power electronic energy source in coordination with an energy source, with a slow dynamic response. It is seen that this scheme is able to quickly recover the grid voltage after a considerable load step change. Simulation has shown that the method makes it possible

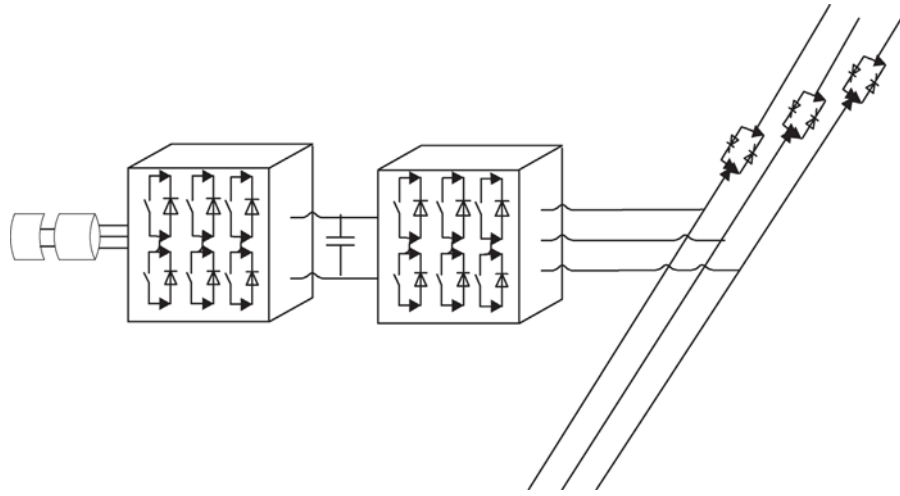


Fig. 7. A grid-interfaced DG system which is isolated from the utility supply during dips by a static transfer switch [29].

to regulate the grid voltage at its nominal value and also control the power sharing between the active filter and the local supply.

4.1.5. DSTATCOM compensators with DG

Wasiak et al. [34] discuss DSTATCOM compensators with distributed generation. DSTATCOM compensator is a shunt connected device of the configuration of 6-pulse Semiconductor Bridge like in conventional STATCOM (Static Synchronous Compensator) systems applied in HV transmission networks. These two groups of devices differ in power; the type of semi-conductor switches applied and their control systems. DSTATCOM controllers are designed for distribution grids and are the members of the custom power device family which provides solutions to the problem of voltage dips.

The working principle is to inject a set of three unbalanced compensating currents to the network such that the network current becomes sinusoidal balanced and in phase with the voltage. The compensator performing such task operates in a current control mode. Its disadvantage include unbalance compensation in 4-wire network requires 4-leg device to be applied, whereas the remaining tasks may be effectively performed by 3-leg compensator.

DSTATCOM compensator is a flexible device which can operate in current control mode for compensating voltage variation, unbalance and reactive power and in voltage control mode as a voltage stabilizer. It is an efficient means for mitigation of voltage dips disturbances introduced to the grid by DGs. However, in some cases the connection of single-phase DGs to the grid may deteriorate power quality considerably.

Another scheme with DSTATCOM, a three-phase voltage source converter (VSC) is implemented as a front end of a DG unit. The D-STATCOM is a voltage source inverter (VSI) used to regulate and balance the voltage at the distribution bus using reactive power injection. The controller is composed of two cascaded controllers, an inner current controller and an outer voltage controller. The outer controller is implemented in both positive and negative sequence frames to be able to compensate for voltage imbalance. A voltage regulation feature was added to the VSC controller in order to maintain the voltage at the load bus equal to the nominal voltage even in case of inverter balanced or unbalanced voltage dips. The VSC is connected to a weak grid through an LCL-filter, to eliminate the higher-order harmonics of the current on the grid side [35].

The DC – link voltage is considered in two ways, viz. as a constant or stiff DC voltage source, and as regulated or weak DC voltage with a constant current source. The control system for the DG unit is

implemented in a rotating dq-frame that is synchronized with the voltage at the PCC using a phase locked loop. The main controller consists of three cascaded controllers, to increase the stability margin and at the same time to damp the oscillations at the resonance frequency of the LCL-filter. The advantage of VSC as a front end is that it enhances the system reliability in weak grids as seen by customers. However, the limited rating of the DG results in limiting the voltage regulation margin.

4.1.6. Decoupling device (FDD)

A novel method of voltage dip mitigation using a resonant device, called the fault decoupling device (FDD) and the current pumping device (CPD) is reported by Cataliotti et al. [36]. The presence of DG units and the FDD allows one to obtain various benefits such as a reduction of the fault current in each node of the network and an increase in the voltage at the DG unit node. It is installed between the substation and the loads. The series-connected inductors and the capacitors are designed in order to realize parallel resonance at the fundamental frequency.

When a current above a threshold is detected by the control system, the static devices in parallel with the inductors are fired in order to shortcut them, while those in series with the capacitors are turned off. During a short circuit on a feeder supplied by the substation, the control system inserts the FDD by turning off the static devices on the faulted line and turning on those in series with the capacitors. The following benefits are obtained:

- (1) A reduction of the short-circuit current on the faulted line;
- (2) A mitigation of the voltage dip at the point of common coupling (PCC);
- (3) A decrease in the short-circuit current drawn from the DG connected to the distribution system;
- (4) An increase in the voltage at the PCC where the DG unit is connected, thus avoiding the activation of anti-islanding protection.

4.2. Intelligent approach for voltage dip mitigation using DG

A voltage dip is caused by a transient process in an electrical network and is stochastic in nature. Several schemes have been proposed for mitigating the voltage dip. When a fault occurs, voltage magnitudes change, artificial intelligence can be applied for detecting the dip incident. Detection at the beginning of the incidence is necessary [37]. A common disadvantage in existing schemes is that

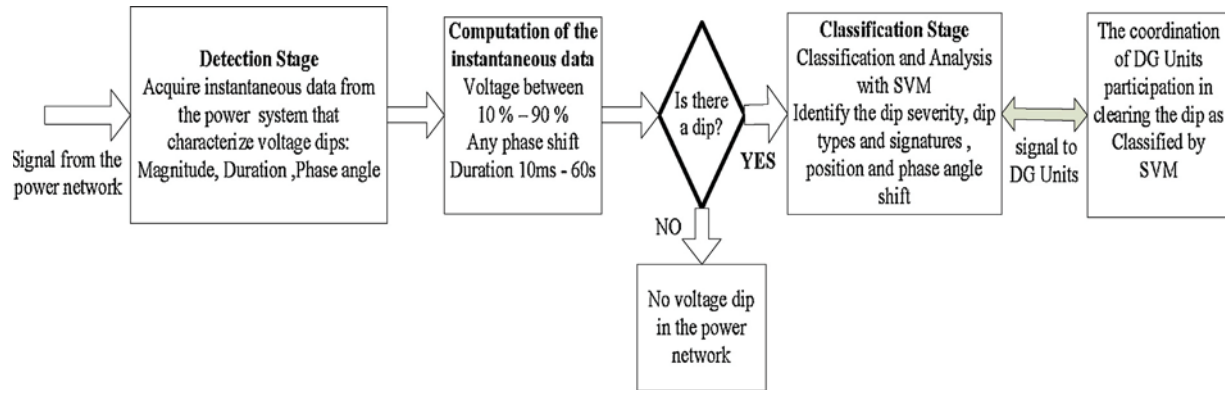


Fig. 8. Architecture of the intelligent approach.

an in-depth knowledge of the process is required for the compensation of the voltage drop. A solution to this is the use of intelligent systems that are able to adjust their dynamic response to any operating condition. The architecture of the intelligent approach is shown in Fig. 8. In technical literature, an intelligent system is viewed as a system that perceives its environment and accordingly takes actions to maximize its chances of success. These systems and techniques are collectively termed Artificial Intelligence (AI). Common AI tools that are mostly used for power system control are fuzzy logic (FL), neural network (NN), genetic algorithm (GA), expert system (ES) and support vector machine (SVM). The advantage of intelligent technique might be:

- (1) Its ability to generalize at high speed.
- (2) It possesses learning ability and is appropriate for non-linear modeling.
- (3) It has shown great ability to synthesize complex mappings accurately and rapidly in a power system.
- (4) It can learn from experience.
- (5) It can handle noisy and incomplete data.

4.2.1. Optimal DG allocation and sizing for mitigating voltage sag in distribution systems

The characteristics of voltage dip in distribution networks caused by faults are highly influenced by the placement and size of DG. The use of particle swarm optimization (PSO) technique to establish the optimal DG allocation and sizing on a distribution network for voltage dip mitigation is presented by [38]. Since voltage dip depends on variety of parameters such as the location of faults, the load type and sensitivity and impedances of the network. The use of PSO technique shows an improvement on voltage dip mitigation when DG was optimally positioned and sized. It is important to find optimal DG location in other to mitigate voltage dips and decrease economic losses experienced with some buses during voltage dip conditions. Genetic Algorithm was used by [14] for optimal placement and sizing of DG for loss reduction and voltage dip mitigation with the presence of DG. The authors of [4] using genetic algorithm propose a new formulation of the optimization objective for designing an optimal DG placement to minimize the effect of voltage dip in a low voltage distribution. The algorithm attempts to simultaneously determine the suitable number of DGs, their sizes and bus locations for a given distribution network. This new method considers both the technical and the economical objectives. The technical objectives involve line loss minimization and voltage dip reduction and minimization of node voltage deviation in the distribution network. The economical objectives include minimization of the actual costs involved in installation and maintenance costs of DG.

4.2.2. Dynamic voltage restorer (DVR) with AI

The configuration and control scheme for the DVR varies depending upon the nature and characteristics of the load to be protected. For a distribution network with sensitive load, [39] demonstrated how a minimum energy can be injected using a simple structure feed forward neural network for separating the negative sequence components from fundamental sequence components in unbalance voltage dip and also correct the voltage dip in a distribution feeder. Industries with induction motor loads require a completely different approach for the design and control of a suitable DVR owing to the inherent inertia of the induction motors as proposed by. Riyasat et al. [40]. A fast-acting, simple and efficient controller is proposed for fulfilling the voltage restoration method with fuzzy logic for industrial induction motor loads during the voltage dip. Ref. [41] shows how an adaptive PI control of dynamic voltage restorer using fuzzy logic can be used to mitigate voltage dip and other voltage disturbances. The aim of the control system is to maintain constant voltage magnitude at the point where the sensitive loads are connected, under system disturbances. The proposed controller combines fuzzy logic to classical PI controller to adjust online PI gains. The main advantage of adaptive fuzzy PI controller over the classical one (PI) is its ability to compensate notching when the DVR is connected to a weak power system. In addition, adaptive fuzzy PI controller improves performance of the DVR and solves the problem of PI tuning.

5. Conclusion

The conventional utility network was not previously designed to accommodate renewable distributed generation (DG) units and high penetration of DG has made the power network more complex in terms of managing its operation, control and protection. At present, the distribution network where most of these DG units are sited do not have enough controller for effective operation and especially controlling the DG units reactive power as a result of voltage dip.

High penetration of DG units will require a more coordination of the distributed generation to mitigate any voltage dip on the power system. The degree of DG penetration can affect the power system negatively rather than mitigating the voltage dips. The major problem occurs when DG units are not properly coordinated during the voltage dip. Distributed algorithm can also be used to control distributed generators without relying on a centralized decision maker as proposed by Stanton et al. [42]. In addition, Illindala et al. [43] shows how to control distributed generation systems to mitigate imbalances due to load conditions and voltage dips from system faults.

To improve the electrical power network performance and get rid of voltage dips is very expensive and might be probably

practically impossible, especially with the present of sensitive loads. Modern systems for power quality mitigation require fast and reliable detection of voltage dips. In this paper, a comprehensive review of different schemes used for voltage dip mitigation through DG deployment, and other schemes has been presented. The advantages and disadvantages of most schemes were highlighted. It also suggested the use of artificial intelligent to enhance voltage dip mitigation.

Most of the schemes presented in many of the research papers have reported mainly on the basis of computer simulations. The simulation results might be good enough for a guideline but this need validation through real time experiments at practical operating conditions.

The grid strength in many developing countries is very weak. This is due to the high demands of electrical power than can be generated. The imbalances in the network system lead to power system instabilities, including frequency and voltage instabilities. Many of the countries experience planned and unplanned load shedding, hence the commercial operations are affected, as are the economies of industrialized countries' and lifestyles of their populations. The penetration of DG units might pose a more problem than supporting the grid and mitigating voltage dip, but the use of intelligent techniques with DG might mitigate voltage dip better. This work is ongoing, the modeling and simulation of the proposed scheme and results will be validated and reported in due course.

Further work needs to be carried out on the classification and transient analysis of voltage dips using latest technology and tools [44]. There is a need for development of control methodologies for fast acting mitigation of voltage dip for achieving the voltage regulation at the consumer premises within regulatory bandwidths.

Acknowledgements

The authors are pleased to acknowledge the support provided by The University of Cape Town, South Africa, Energy Reliability & Security Research Laboratory, Michigan State University, Eskom Holdings Limited, South Africa and Ipinimo Oluwayemisi.

References

- [1] E. Newman, B.A. Carreras, M. Kirchner, I. Dobson, The impact of distributed generation on power transmission grid dynamics system sciences, in: HICSS, January, 2011, pp. 1–8.
- [2] N. Nimpitiwan, Inverter-based photovoltaic distributed generations modelling and dynamic simulations, in: TENCON, November, 2010, pp. 7–12.
- [3] A.H. Parsaifard, M. Manbachi, M.B.A. Kopayi, M.R. Haghifam, A market-based generation expansion planning in deregulated environment based on distributed generations development, in: Probabilistic Methods Applied to Power Systems (PMAPS), June, 2010, pp. 677–684.
- [4] B. Soma, K.G. Swapan, C. Amitava, Optimum distributed generation placement with voltage sag effect minimization, ELSEVIER, Energy Conversion and Management 53 (2012) 163–174.
- [5] A. Saidian, D. Mirabbasi, M. Heidari, The effect of size of DG on voltage flicker and voltage sag in closed-loop distribution system, in: Industrial Electronics and Applications (ICIEA), June, 2010, pp. 68–72.
- [6] L. Paul Joskow, Lessons learned from electricity market liberalization, The Energy Journal IAAE (2008) 9–42 (special issue).
- [7] Electrotek Concepts, 2012, Available online: <http://www.electrotek.com/voltsag.htm>
- [8] M.H.J. Bollen, 'Understanding Power Quality Problems': Voltage Sags and Interruptions, Wiley-IEEE Press, 2000.
- [9] A.A. Eajal, M.E. El-Hawary, Optimal capacitor placement and sizing in unbalanced distribution systems with harmonics consideration using particle swarm optimization, IEEE Transactions on Power Delivery 25 (July) (2010) 1734–1741.
- [10] G.N. Koutroumpetis, A.S. Safigianni, G.S. Demetzos, J.G. Kendristakis, Investigation of the distributed generation penetration in a medium voltage power distribution network, International Journal of Energy Research 34 (2010) 583–593.
- [11] A. Bracale, P. Caramia, G. Carpinelli, A. Russo, P. Verde, Site and system indices for power-quality characterization of distribution networks with distributed generation, IEEE Transactions on Power Delivery 26 (3) (2011) 1304–1316.
- [12] A.G. Madureira, J.A. Peças Lopes, Ancillary services market framework for voltage control in distribution networks with microgrids, ELSEVIER, Electric Power Systems Research 86 (May) (2012) 1–7.
- [13] R. Angelino, G. Carpinelli, D. Proto, A. Bracale, Dispersed generation and storage systems for providing ancillary services in distribution systems, in: Power Electronics Electrical Drives Automation and Motion (SPEEDAM), 2010, pp. 343–351.
- [14] S.M. Farashbashi-Astaneh, A. Dastfan, Optimal placement and sizing of DG for loss reduction, in: voltage profile improvement and voltage sag mitigation, International Conference on Renewable Energies and Power Quality (ICREPO), March, 2010.
- [15] K. Honghai, L. Shengqing, W. Zhengqiu, Discussion on advantages and disadvantages of distributed generation connected to the grid, in: Electrical and Control Engineering, International Conference ICECE, 2011, pp. 170–173.
- [16] M.H.J. Bollen, K. Stockman, R. Neumann, G. Ethier, J.R. Gordon, K. van Reussel, S.Z. Djokic, S. Cundeva, Voltage dip immunity of equipment and installations – messages to stakeholders, in: Harmonics and Quality of Power (ICHQP), IEEE 15th International Conference (June), 2012, pp. 915–919.
- [17] M.A. El-Gammal, A.Y. Abou-Ghazala, T.I. El-Shennawy, Voltage sag effects on the process continuity of a refinery with induction motors loads, Iranian Journal of Electrical and Computer Engineering 9 (1) (2010) 67–72.
- [18] S. Cundeva, R. Neumann, M. Bollen, Z. Kokolanski, Immunity against voltage dips, main recommendations to stakeholders of the CIGRE/CIREU/UIE Joint Working Group C4.110, International Journal of Emergency Science 1 (December (4)) (2011) 555–563.
- [19] A. Honrubia-Escribano, E. Gómez-Lázaro, A. Molina-García, J.A. Fuentesb, Influence of voltage dips on industrial equipment, Analysis and assessment, Elsevier, International Journal of Electrical Power & Energy Systems 41 (October (1)) (2012) 87–95.
- [20] S. Bhattacharyya, S. Cobben, W. Kling, Proposal for defining voltage dip-related responsibility sharing at a point of connection, Generation, Transmission & Distribution, IET 6 (7) (2012) 619–626.
- [21] F. Pilo, G. Pisano, G.G. Soma, Considering voltage dips mitigation in distribution network planning power tech, in: IEEE, Lausanne, July, 2007, pp. 1528–1533.
- [22] J.A. Martinez-Velasco, J. Martin-Arnedo, Distributed generation impact on voltage sags in distribution networks, in: 9th International Conference on Electrical Power Quality and Utilization, (EPQU), 2007, pp. 1–6.
- [23] Derek Maule Claude, Power Quality Application Guide Voltage Dip Mitigation, 2012, Available: <http://www.copperinfo.co.uk/power-quality/downloads/pqug/532-voltage-dip-itation.pdf>
- [24] D. Gaikwad, S. Mehraeen, Reactive power considerations in reliability analysis of photovoltaic systems, in: Green Technologies Conference, 2012 IEEE, April, 2012, pp. 1–6.
- [25] B. Renders, K. De Gussemé, W.R. Ryckaert, K. Stockman, L. Vandevelde, M.H.J. Bollen, Distributed generation for mitigating voltage dips in low-voltage distribution grids, IEEE Transactions on Power Delivery 23 (July) (2008) 1581–1588.
- [26] K.S. Ramesh, K. Ritesh, M. Venmathi, L. Ramesh, Analysis of voltage sag with different DG for various faulty conditions, in: Proceedings of the International Joint Conference on Engineering and Technology (IJJCET), 2010.
- [27] O. Ipinimo, S. Chowdhury, S.P. Chowdhury, Application of grid integrated wind energy conversion systems for mitigation of multiple voltage dips in a power network, in: Universities Power Engineering Conference Proceedings 46th International, (UPEC), September, 2011, pp. 1–6.
- [28] S. Surisunthon, T. Tayjasanan, Impacts of distributed generation on voltage sag assessment in distribution systems, in: Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), May, 2011, pp. 889–892.
- [29] K.J.P. Macken, H.J. Bollen, R.J.M. Belmans, Mitigation of voltage dips through distributed generation systems, IEEE Transactions on Industrial Applications 40 (2004) 1686–1693.
- [30] R.S. Bajpai, R. Gupta, Series compensation to mitigate harmonics and voltage sags/swells in distributed generation based on symmetrical components estimation, Industrial Electronics (ISIE), IEEE International Symposium (2011, June) 1639–1644.
- [31] X. Liu, P. Li, The effect of DVR on distribution system with distributed generation, in: Proceedings of International Conference on Electrical Machines and Systems, 2007, pp. 277–281.
- [32] T. Vandoorn, J. De Kooning, B. Meersman, J. Guerrero, L. Vandevelde, Voltage-based control of a smart transformer in a microgrid, IEEE Transactions on Industrial Electronics 99 (2011) 1–14.
- [33] F. Carastro, M. Sumner, P. Zanchetta, Mitigation of voltage dips and voltage harmonics within a micro-grid, using a single shunt active filter with energy storage, in: Proceedings of 32nd Annual Conference on IEEE Industrial Electronics, (IECON), 2006, pp. 2546–2551.
- [34] I. Wasiak, R. Mienski, R. Pawelek, P. Gburczyk, Application of DSTATCOM compensators for mitigation of power quality disturbances in low voltage grid with distributed generation, in: EPQU, 2007, pp. 1–6.
- [35] F. Magueed, H. Awad, Voltage compensation in weak grids using distributed generation with voltage source converter as a front end, in: IEEE PEDS, 2005, pp. 234–239.
- [36] A. Cataliotti, G. Cocchiara, M.G. Ippolito, G. Morana, Applications of the fault decoupling device to improve the operation of LV distribution networks, IEEE Transactions on Power Delivery 23 (1) (2008) 328–337.
- [37] O. Ipinimo, S. Chowdhury, S.P. Chowdhury, J. Mitra, Intelligent voltage dip detection in power networks with distributed generation (DG), in: NAPS, September, 2012, pp. 1–6.

- [38] O.M. Amanifar, E.H. Golshan, Optimal DG allocation and sizing for mitigating voltage sag in distribution systems with respect to economic consideration using Particle Swarm Optimization, in: *Electrical Power Distribution Networks*, EPDC, May, 2012, pp. 1–8.
- [39] M.R. Banaei, S.H. Hosseini, M.D. Khajee, Mitigation of voltage sag using adaptive neural network with dynamic voltage restorer, in: *Power Electronics and Motion Control Conference, IPEMC*, August, 2006, pp. 1–5.
- [40] A. Riyasat, H. Ashraful, A fuzzy logic based dynamic voltage restorer for voltage sag and swell mitigation for industrial induction motor load, *International Journal of Computer Applications* 30 (September (8)) (2011) 0975–8887.
- [41] B. Ferdi, C. Benachaiba, S. Dib, R. Dehini, Adaptive PI control of dynamic voltage restorer using fuzzy logic, *Journal of Electrical Engineering Theory & Application* 1 (June (3)) (2010) 165–173.
- [42] T. Stanton, D. Alejandro, Distributed generation control of small-footprint power systems, in: *NAPS*, September, 2012, pp. 1–8.
- [43] M. Illindala, U. Venkataramanan, Control of distributed generation systems to mitigate load and line imbalances, in: (PESC), 2002, pp. 2013–2018.
- [44] O. Ipinnimo, S. Chowdhury, S.P. Chowdhury, Voltage dip mitigation with DG integration: A comprehensive review, *power electronics, drives and energy systems*, in: (PEDES), December, 2010, pp. 1–10.