JEPECS
Journal of Electric Power and Energy Conversion Systems
JOURNAL OF ELECTRIC POWER AND ENERGY CONVERSION SYSTEMS (JEPECS)
JEPECS VOL. 1, NO. 3, PP. 107-119, AUTHUM 2016
ISSN: 2345-4830 print/2345-4733 online

Voltage Sag in Distribution Systems- A review and comparative study (Causes, Characteristics, Compensations and Detection)

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By quick technological advancements in industrial control processes, major industries demand higher power quality. According to IEEE 1159-1995 standard, any problems in voltage, current or frequency that lead to the error or malfunctions in electrical equipment are considered as a power quality problem. Among the power quality phenomena, voltage sag has been an important problem for power systems in meeting advanced industries. This phenomenon happens continuously both in transmission and distribution levels. In this paper, following a general review on the voltage sag phenomenon, short circuit faults, starting big inductive motors and energizing of the transformer are considered as the main factors of providing this event. Then voltage sag characteristics are presented. And then the suggested strategies to reduce this event are evaluated. Applying conventional methods for voltage sag compensation is not able to meet this event completely. In recent years, with rapidly developing in semi-conductor industries and control systems, using compensators which are based on controllable electronic devices with higher speed, has attracted many power experts' attentions. At the end, voltage sag compensation style has been studied through applying different compensators.

Keywords:Power Quality, Voltage Sag, FACTS Devices, DFACTS

Received Sep. 2016; Revised Nov. 2016; Accepted Jan. 2017.

I Introduction

In the power private market and sector, respecting power quality standard is considered as a subscriber's index of the competition for the power companies [1,2]. Basically the issue of power quality is important due to the four following reasons [3,4]: (1) Greater sensitivity of the new loads than the power quality and quantity changes of power, (2) Using power electronic devices to increase efficiency and thus the harmonic level in the network, (3) Greater awareness of the users regarding the issue of power quality and (4) Connection of electronic equipment through networks and their mutual influences. On the manufactures' view, power quality is defined as reliability and on the view of the manufactures of the electronic equipment is as the power supply criteria and characteristics in such a way that the related equipment and tools work properly on those conditions [5]. On the users' view power quality is an issue related to the users. Power distribution systems are always at the edge of this destructive elements of sinusoidal move forms (voltage and current) such as voltage sag, voltage swell, interruption and etc. [6,7]. These phenomena decrease the power quality and network reliability [8,9]. These ones are the disturbances which are mainly imposed by the users to the network and the occurrences of such disturbances have some negative effects on the other users and network equipment [10,11]. Voltage sags are related to power quality problems [12,13]. In electrical power distribution system near above 92% of all disturbances are due to the voltage sag. These are usually the results of faults in power system and switching action in isolate the faulted line [14,15]. Various research papers and thesis reports have been done on the subject of voltage sag in distribution systems [16,17]. This paper gives an overview of voltage sag reasons, its compensation and methods used in the mitigation of voltage sags. This paper is organized as follows: Section II will present a literature review about power quality events. Section III will deal with a brief introduction of the voltage sag reasons. A voltage sag is normally characterized by magnitude, duration and frequency. In the section IV, the voltage sag characteristics are expressed. Several methods for the mitigation of voltage sag have already been reported and reviewed. Section V will describe the methods for the reducing of voltage sags. Voltage sag detection is very important as it determines the dynamic performance of the voltage sag regulator. In section VI is described the voltage sag detection. The summary will end with conclusions in section VII.

II Power quality events

Power quality issues are essential for proper operation in industrial processes disturbances which involve critical and sensitive loads such as voltage sags and swells, short duration interruptions, harmonics and transients may disrupt the processes and lead to considerable economic loss [18]. In this part, three important events of power quality are defined based on IEEE 1159-

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Published by Shahed University Publishing Center.

1995 standard [19]. A fault on the power system will cause both a decrease in voltage magnitude and a shift in phase angle [20]. Voltage sag has much a global problem. Voltage sag or temporary loss of voltage is the 0.1-0.9 pu decrease in the effective amount of voltage at the power frequency for duration half a cycle to 1 min [21,22]. Sag duration time is between the starting point of voltage sag to end point of voltage sag. The voltage sag duration is the period of time in which the voltage is lower than a stated limit, as shown in Fig. (1-a). The detection threshold is also represented (V=90%). Normally, sag duration is less than 1 sec. Voltage swell is the opposite of a sag. Voltage swell is the increase in the effective voltage at the power frequency for duration half a cycle to 1min. Values are usually between 1.1-1.8 p.u [23,24], as shown in Table 1. Power interruption is a short-time change and complete loss of voltage (¡0.1p.u.) in one or more phase conductors is for duration half a cycle to 3 sec [25]. Fig. (1-b) shows those sample events classified as the voltage sag, voltage swell and interruption .Voltage sag starts when one of the effective voltages decrease to lower than the threshold value and it finishes when the three values of effective voltage return to higher than the threshold value . Voltage sag threshold is selected as 90% of reference voltage and voltage swell starts when one of the smallest effective voltages increase to a higher threshold and stops when the three effective voltages return to lower than the threshold value. Voltage swell threshold is selected as 110% of the reference voltage. Interruption starts when the three effective voltages decrease to lower than the threshold value and finishes when one of the smallest one of theirs returns to higher than the threshold . Interruption threshold is selected as 10% of the reference voltage. Fig. (1-c) describe the demarcation of the various power quality issues defined by IEEE Std. 1159-1995. As the voltage sag is one of the most important problems of power companies regarding the industries and includes about 80% of the power quality problems. Voltage sag can have significant economic consequences for different types of industrial applications and utility distribution networks.

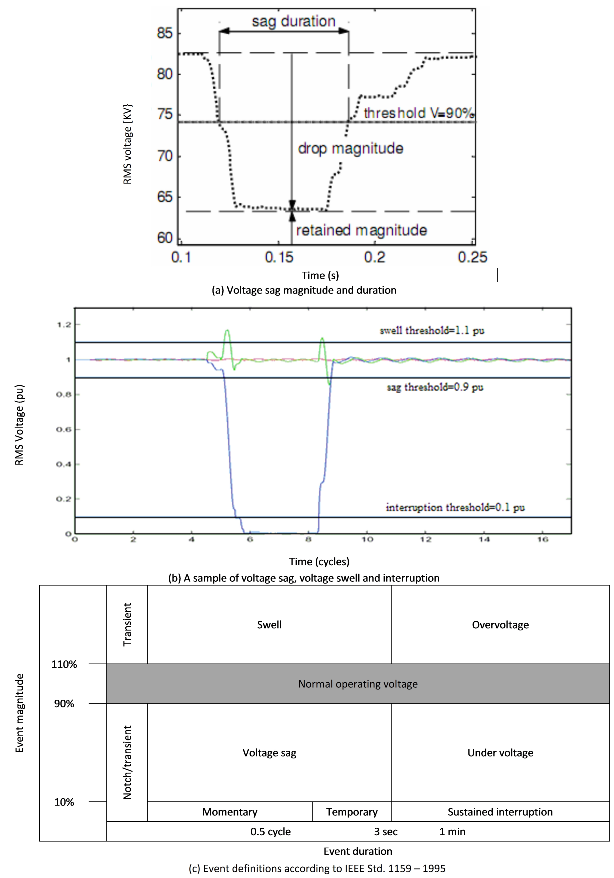


Figure 1: Power quality events

III VOLTAGE SAG CAUSES

By great and quick technological advancements in industrial control processes, major industrial consumers demand higher power quality [26,27]. Among all the classifications of electrical disturbances, voltage sag is a nightmare for automatic processes [28,29]. Following great researches of the experts, it is found that 85% of the malfunctions of the power supply (that is attributed to weak power quality) are due to voltage sag [30,31]. Based on the issued topics regarding voltage sag, this one is classified as a temporary low and medium frequency phenomenon. This part reveals the reasons of this phenomenon and computation methods. Voltage sags associated with faults in transmission and distribution systems, energizing of transformers, and starting of large induction motor are considered as most important power quality disturbances (PQD) [32,33].

A *Short circuit faults*

One of the most important reasons of voltage sag phenomenon is short circuit fault, which unsymmetrical faults like single-phase to ground short circuit includes a greater amount than the symmetrical faults which rarely occur in power systems [34,35]. To determine voltage sag domain in radial networks, it is possible to use voltage divider model. This circuital model is shown in Fig. (2-a), where ZS is the source impedance in the point of common coupling (PCC), ZF is the impedance between PCC and the fault position [36,37]. Voltage in PCC bus and equipment terminal is given by [38]:

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{1}$$

From the above equation we can find out that voltage sag is deeper where the fault occurs close to the customer (lower Z_F) and in systems with the lowest fault level (higher ZS) [39]. To calculate voltage sag domain in a looped system and based on Tevenin theorem, the voltage sag in i bus which is created in r bus through the fault is given by the following equation [40].

$$V_{sag,i} = V_{o,i} - \frac{Z_{ir}}{Z_{rr} + Z_F} V_{o,r} \tag{2}$$

where $V_{sag,i}$ and $V_{sag,r}$ are the voltage sags during the faults in i and r bus respectively . The values of $V_{o,i}$ and $V_{o,r}$ are the voltages before the faults. Z_{rr} and Z_{ir} are the elements in the bus impedance matrix and Z_F is the fault impedance. For a fault in the transmission system, customers do not experience interruption, since transmission systems are looped or networked.

Fig. (2-b) shows voltage sag on all three phases due to a cleared single-phase to ground fault.

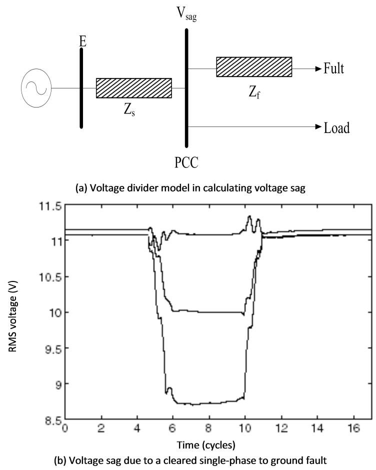


Figure 2: Voltage sag causes (Short circuit faults)

B Starting large induction motors

Among the other major casess of voltage sag phenomenon (that is more related to industrial power systems) are starting large induction motors [41]. While starting an induction motor, a greater current is taken from the system in normal mode (generally 5 or 6 fold) [42]. This current remains until the motor reaches its nominal speed which lasts about several seconds to 1 min [43,44]. In this situation, voltage sag is strongly related to the system parameters. Then consider system depicted in Fig. (3-a), where Z_s is the source impedance and Z_M is the motor impedance while starting. The created voltage sag on the bus that feeds the motor and load is obtained through the following voltage divider equation [45]:

$$V_{sag} = \frac{Z_M}{Z_S + Z_M} E \tag{3}$$

In this case, the motor and source impedances while starting are obtained as the following, as the motor in its nominal power of S_{motor} is fed through the short circuit power of S_{source}:

$$Z_s = \frac{V_n^2}{S_{sourcs}} \qquad Z_M = \frac{S_{source}}{\beta S_{motor}} \tag{4}$$

where β is the ratio of starting current and nominal one. In this case (3) is written as:

Table 1: Definitions for voltage sag and swell

type of disturbance	typical magnitude	typical duration	causes
voltage sag	0.1-0.9 pu	0.5-30 cycles	starting heavy loads - ground faults
voltage swell	1.1-1.8 pu	0.5-30 cycles	load rejection

$$V_{sag} = \frac{S_{source}}{S_{source} + \beta S_{motor}} \tag{5}$$

This amount can be used to estimate the voltage sags due to starting inductive motors. Voltage sag duration due to starting motor is related to motor parameters, among which the motor inertia is the most significant one [46]. When the starting time of the motor is determined, then determining sag domain in the terminal of the motor becomes more important. The created torque of the motor is related to the square of the terminal voltage. Assuming that the terminal voltage is a nominal one, the mechanical torque is half of the electrical one during the longest starting time. When the voltage decreases to its 90% nominal value, then the electrical torque decreases to its 81% nominal value which is 162% of the mechanical torque. The accelerating torque, the difference between the electrical and mechanical torque, decreases from 100% to 62% which leads to a doping of 38% [47]. Fig. (3-b) shows a stator line current after the occurrence a three phase short circuit on the stator terminals for a 5 cycle's duration. This is equal to voltage sag of 100% [48].

C The energizing of the transformer

Transformer is an indispensable component of power system which performs many functions such as electrical isolation, noise decoupling, voltage transformation and power quality improvement [49]. The energizing of the transformer is another reason for the creation of voltage sag phenomenon in power systems. Its result is an inrush current that finally decreases to a small magnetizing current. The needed time to decrease this inrush current relates to the magnetizing reactance of the transformer. In such a condition, the inrush current reasons a temporary voltage loss in the network impedance which is between the supply and energizing transformer. Unlike the short circuit faults, energizing a distribution transformer is a predictable practice, therefore the sensitive loads should be protected against this voltage sag. Restoring the voltage after any voltage sag phenomenon saturates the transformer and this creates an inrush current like the one of energizing of the transformer. Sometimes, for long duration voltage sags, more transformers are driven into saturation. This is called sympathetic interaction. Fig. (4-a) show the voltage sag due to transformer energizing [50]. Fig. (4-b) shows the equivalent circuit of a single-phase transformer [51]. Here it is possible to use a simple method to get the maximum inrush current and the created voltage sag due to energizing of the transformer. In these conditions the inrush current does not exceed the following equation:

$$I_{Inrushmax} = \frac{E}{X + X_p + X_C(min)} \tag{6}$$

where X, is the source reactance at the bus which the transformer is energized. The minimum magnetic reactance, $X_C(min)$, shows the maximum flux possibility after energizing of the transformer. It is assumed that the iron core reactance is twice the short circuit impedance. In the other word, the impedance $X_C(min)$ is typically the same value as $2(Xp+Xs)$ or $2X_T$ [52]. Assuming the leakage reactance in each winding equal, the maximum voltage sag can be calculated by the following:

$$V_{sag} = \frac{X}{X + 2.5X_T} \quad (7)$$

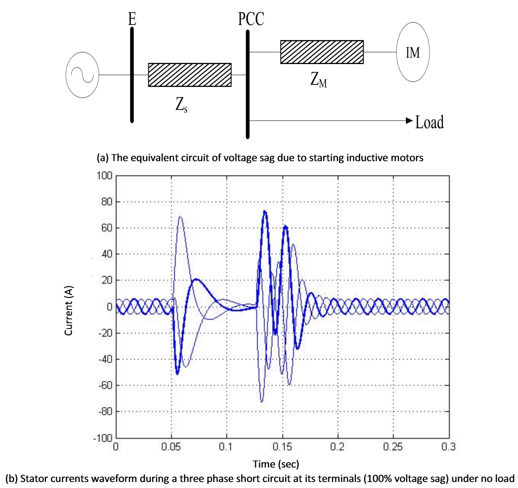


Figure 3: Voltage sag causes (Starting a large induction motor)

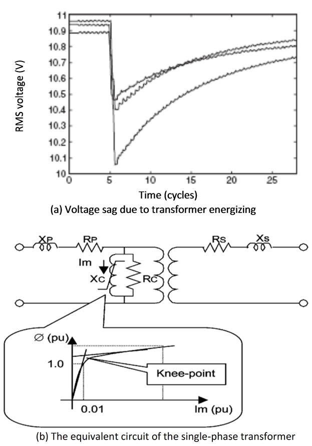


Figure 4: Voltage sag causes (Energizing of a transformer)

IV VOLTAGE SAG CHARACTERISTICS

Any voltage sag phenomena are determined with these three factors of domain (retained voltage), duration and phase angle jump [53]. These are the most important and main characteristics that determine the behavior of the equipment. The domain (retained voltage) in voltage sag is the least effective voltage in each of the three phases. This one relates to the sensitivity of the equipment. The domain is determined by the electrical distance to the fault position. The effective factors in determining the domain are expressed as fault position, fault type, fault impedance, load conditions, the effects of the transformer connections and the voltage before the fault [54,55]. In most cases, the magnitude of the sag is down to 60% to 70% of nominal load voltage. The magnitude of measured voltage sags at an industrial plant supplied from a 115 kV system is show in Fig. 5. Calculating method of voltage sag domain is expressed in section of the voltage sag reasons.

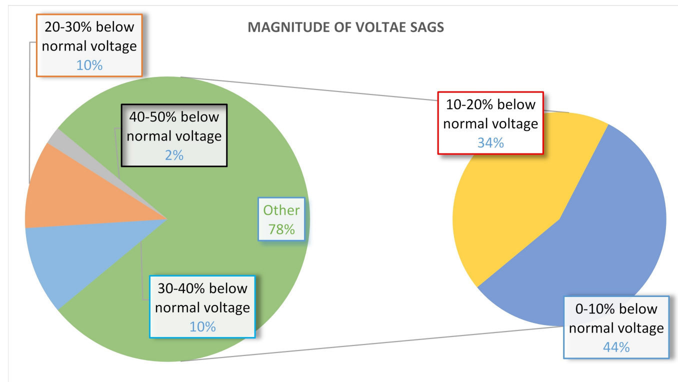


Figure 5: Magnitude of measured voltage sags at a industrial plant

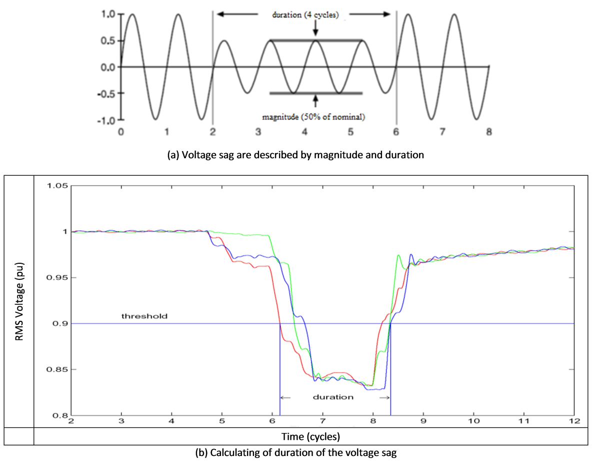
Typical sags are described in terms of magnitude and duration as shown in Fig. (6-a) [56]. In a three-phase system, the voltage sag duration is the duration when one of the least effective values of voltages is below the voltage sag threshold (90% of its nominal value). Voltage sag starts when one of the effective values of the voltage decrease to lower than the threshold and ends when all the effective three-phase voltages return to upper than the threshold. This duration can be calculated as the difference between the time when all the effective voltages return to upper than the threshold and the time when one of the least values of effective voltages decreases to lower than the threshold [33]. This duration is determined by time of the fault removal. Therefore, the above characteristic depends on the operations of the protection equipment and how long the fault current is allowed to pass [57]. Fig. (6-b) shows the calculation style of this duration. Not only the voltage domain decreases, but also changes the voltage phase angle that is called phase angle jump, and is the third characteristic in any voltage sag phenomenon. Phase angle jump means that the phase angle during voltage sag and before it is different. Phase angle jump is defined with the voltage basic component method as the following [58]:

$$V_{fin}(t) = \frac{2}{T}\int_{t-\tau}^{t} v(\tau)e^{j\omega\tau}d\tau \quad (8)$$

where ω and T is a cycle of the main frequency. Phase angle jump and domain are directly related to the voltage in fault phases or among them, in the point of common coupling (PCC) between the fault and load. The characteristic of voltage dips in power systems with special emphasis for different types of unbalanced dips and electrical components analysis is show in [59].

V STRATEGIES FOR MITIGATION OF VOLTAGE SAGS

Due to the applying sensitive equipment in modern industrial designs such as process controllers, programmable logic control (PLC), adjustable speed driver (ASD) and robots, the voltage

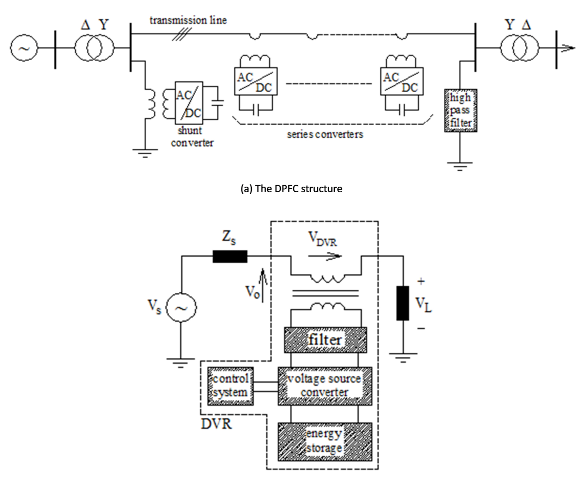


(a) Voltage sag are described by magnitude and duration

(b) Calculating of duration of the voltage sag

Figure 6: Voltage sag characteristics

sag phenomenon is not tolerated in power system and various methods have been applied to decrease this phenomenon. The conventional methods include using capacitor banks, installing new parallel feeders and uninterruptable power supply (UPS) [60]. Applying these methods doesn't solve the power quality problems, and they lead to uncontrollable reactive power compensation, more costs in installing new feeders and using UPS [61,62]. Another method to decrease voltage sag phenomenon is using current limiting fuses [63]. In these fuses, voltage sag in the system can be reduced by limiting the current passing time and quick cutting of the connection. Setting and proper synchronizing of relays and fuses (generally, protection devices) can help modify this phenomenon. It's worth noting that about 50% of the issues related to voltage sag deal with the protection behavior and their interactive influences on each other and the imposed voltage sag from the neighboring feeders with the same supply. Another reducing method is feeder transmission in the distribution system that is done through switching and includes two steps. At first the weakness points for voltage sag are determined through risk assessment method and by reliable data, voltage sag domain and time and influence coefficients on the customers. The next step includes transmitting these weak points to the other sources during fault current flow. In this step, Mont Carlo method and reliable data are used, too [64,65]. The genetic-algorithm (GA)-based optimization software for reconfiguration of a distribution network in order to minimize financial losses due to voltage sags is described in [66], which fault analysis is performed to first calculate voltage sags at different buses and then to calculate financial losses incurred by voltage sags at buses with sensitive industrial processes. In recent years based on quick advancements in semi-conductor industries and control systems applying those compensators which are based on current and voltage source converters, have attracted the power experts' attention [67,68]. This equipment which have been first introduced by N.G. Hingorani in 1995 are known as flexible AC transmission systems (FACTS) which are called as DFACTS devices in distribution networks, that can do the compensation rapidly, immediately and controllably [69,70,71,72]. In [73] is investigated concurrently operation between the distributed static series compensator (DSSC) and the static synchronous compensator (STATCOM) in power systems. Also in paper [74] is proposed a distribution-unified power flow controller (D-UPFC) for preventing both voltage sag and swell conditions. FACTS devices is originally developed for transmission networks but similar ideas are now starting to be applied in distribution systems [75,76,77]. Applying these devices has increasingly attracted the power engineers' attention to reduce power quality problems [78,79]. Due to the studies to decrease voltage sag, using two kinds of compensators, the parallel and series, are suggested [80,81]. FACTS devices or their sub-derivative custom power devices are efficient and often used for voltage sags mitigation in electrical power system [82,83]. Some of the widely used custom power devices are dynamic voltage restorer (DVR), distribution static synchronous compensator (DSTATCOM) [84,85], active filter (AF) [86,87], unified power quality conditioner (UPQC) [88]. In [89] is investigated three types of FACTS devices which are used in practical applications and then this paper show modeling method and the effectiveness of these devices in sag mitigation, which proposed approach is based on system impedance matrix that incorporates FACTS devices. Different types of power system faults in [90] are simulated on a typical British distribution network model at various locations to obtain voltage sag profiles. In [91] is proposed distributed power flow controller (DPFC) to mitigate the voltage sag and swell, which DPFC in structure is similar to unified power flow controller (UPFC) as shown in Fig. (7-a) [92].



(a) The DPFC structure

(b) Schematic structure of the DVR compensator

Figure 7: DVR and DPFC structure

A Dynamic voltage restorer (DVR)

Dynamic voltage restorer is a static series compensator that is applied to voltage sag compensation in the distribution level [93,94]. This compensator is series equipment that generates ac voltage and injects it through a transformer and in a series manner with the voltage supply to compensate voltage [95]. This

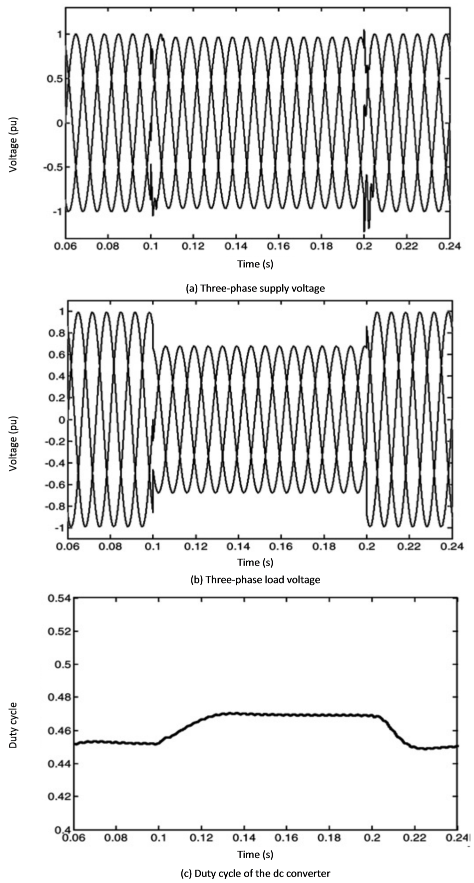


Figure 8: System response because of three-phase 60 percent voltage sag with 288 phase jump - linear load

injected voltage and load current determines the DVR power. The main components of this compensator are: dc supply, voltage source invertor (VSI), injection series transformer and harmonic filter which its circuit diagram is depicted in Fig. (7-b) [96,97]. In [98,99] is proposed a topology for three-phase DVR to compensate the balanced and unbalanced voltage sag and voltage swell, which proposed topology uses direct three-phase to three-phase converter with fictitious DC link. Fig. 8 show the response of the system because of 60% three-phase voltage sag with positive 288 phase jump considering linear and non-linear loads. As a result of that, the PI controller reacts and increases the duty cycle D to keep the output voltage of the dc-to-dc converter constant at the reference setting value as depicted in part c of figure. In [100] is suggested a interline dynamic voltage restorer (IDVR) to eliminate the voltage sag and harmonics, which the IDVR is shown in Fig. 9 is consisted of two DVRs connected to two different feeders. Vb1 and Vb2 are voltages of bus 1 and bus 2 at the distribution side where IDVR is connected. Load 1 and load 2 are connected to each of the buses that are shown with Vl1 and Vl2. From the view point of voltage injection, this compensator can inject the voltage to the system in four methods: in-phase compensation (IPC), pre-dip compensation (PDC), in phase advance compensation (PAC) and voltage tolerance method (VTM) with minimum energy injection [101].

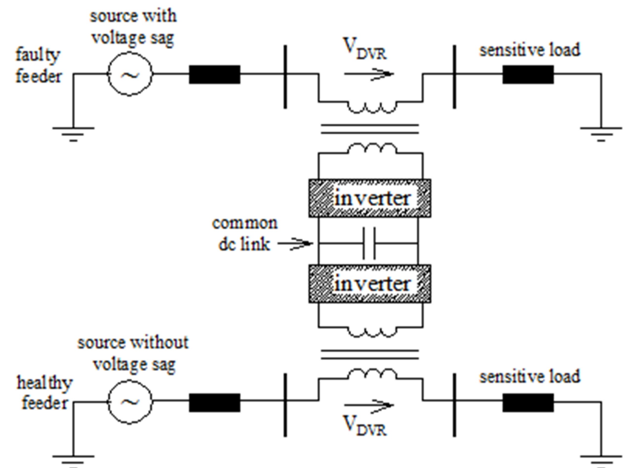


Figure 9: Schematic diagram of IDVR

A.1 In-phase compensation method (IPC)

This is the most popular compensation method with DVR, in which the load voltage during compensation is in phase with source voltage and it is independent from the load current and the voltage before the fault. Phasor diagram of the in-phase compensation method show in Fig. (10-a). In this case, the Si1, injected apparent power and Pi1, injected active power, are as the followings:

$$\begin{aligned} &S_{i1} = I_L V_i = I_L(V_L - V_s) \\ &P_{i1=} I_L V_i \cos\theta_s = I_L(V_L - V_s)\cos\theta_s \end{aligned} \tag{9}$$

where the angle of the injected voltage and domain are:

$$\begin{aligned} &V_{i1} = V_L - V_s \\ &\theta_{i1=}\theta_s \end{aligned} \tag{10}$$

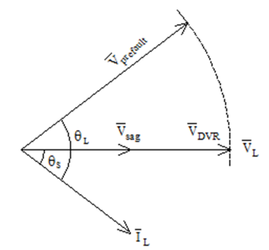
A.2 Pre-dip compensation method (PDC)

Some loads are greatly sensitive to phase angle jump. Phasor diagram of the pre-dip compensation method show in Fig. (10-b). Here it's needed to provide boosted load bus voltage that is in phase with the pre-dip. In this case, S_{i2}, the injected apparent power, and P_{i2}, the injected active power, are determined as [102]:

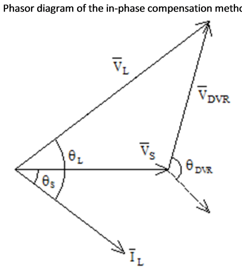
$$\begin{aligned} &S_{i2} = I_L V_i = I_L\sqrt{V_L^2 + V_S^2 - 2V_L V_S cos(\theta_L - \theta_S)} \\ &P_{i2} = I_L(V_L\cos\theta_L - V_S\cos\theta_S) \end{aligned} \tag{11}$$

From the power quality point of view, the PDC method is the best compensation strategy. As in this method the voltage is returned to its pre-dip domain and its phase is not changed, then it can be used to return the load voltage. Therefore the domain and the angle of the injected voltage are respectively as the followings:

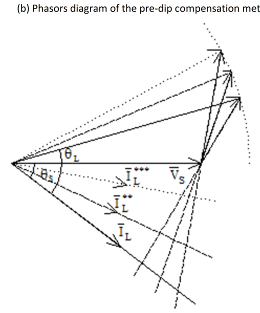
$$V_{i2} = \sqrt{V_L^2 + V_S^2 - 2V_L V_S cos?(\theta_L - \theta_S)}$$
$$\theta_{i2} = \tan^{-1}\left(\frac{V_L \sin\theta_L - V_S \sin\theta_S}{V_L \cos\theta_L - V_S \cos\theta_S}\right) \quad (12)$$



(a) Phasor diagram of the in-phase compensation method



(b) Phasors diagram of the pre-dip compensation method



(c) Phasors diagram of the phase advance compensation method

Figure 10: Phasor diagrams

However, from the above evaluation, it is evident that PAC method is suitable to find the minimum injected active energy. But it is necessary to set the instantaneous phase angle that creates discontinuity wave-shape and load power swing. This issue can be important for sensitive loads. In [104] some topics are suggested regarding the proposed combinatory algorithm of IPC and PAC that can alleviate the aforementioned problem.

A.3 Voltage tolerance method with minimum energy injection

If the voltage magnitude is between 90%-110% of nominal voltage and 5%-10% of nominal state, it will not disturb the operational specification of loads. In this method, both magnitude and phase are the controlable parameters, it can be achieved by small energy injection.

B Distribution static synchronous compensator (DSTATCOM)

The functions of DSTATCOM are harmonic currents elimination drawn by load, limit the active and reactive power oscillations, load balancing in power factor correction and voltage regulation modes [105,106]. If this compensator is used in power transmission systems, then is called STATCOM and if it is used in the distribution systems then it is called DSTATCOM (which is installed near and in a parallel the sensitive loads of the distribution systems) [107,108]. The DSTATCOM is a power electronic-based synchronous voltage generator able to provide fast and continuous capacitive and inductive reactive power supply [109,110]. A DSTATCOM is used to regulate bus voltage on a 25 kV distribution network by absorbing or generating reactive power [Fig. (11-a)]. Without DSTATCOM, bus voltage varies between 0.96 pu and 1.04 pu (4% variation). But with the DSTATCOM Controller, the voltage fluctuation at bus is now reduced to 0.7%. The DSTATCOM compensates voltage by injecting a reactive current as shown in Fig. (11-b), that varying between 0.6 pu capacitive when voltage is low and 0.6 pu inductive when voltage is high. The design considerations of DSTATCOM system and controller for voltage sag compensation is proposed in [111], which the voltage sag compensation performance with different current injection schemes is briefly explained and the interaction is described. A control scheme base on the d-q reference frame for the decoupling of active and reactive current components, for a DSTATCOM aimed at mitigating voltage sag at the PCC or eliminating current harmonics of the load is presented in [112]. DSTATCOMs are used in [113] to compensate the voltage sag induced by loads, which a PI controller is designed to regulate the voltage for a linear DSTATCOM model. The main components of DSTATCOM compensator are depicted in Fig. (11-c) [114,115]. As shown, this compensator includes energy storage, three-phase inverter, ac filter, coupling transformer and control strategy [116,117]. In this diagram the shunt injected current of Ish modifies the voltage sag through adjusting the voltage across the system impedance of Zth. The Ish can be controlled through adjusting the output voltage of the convertor.

$$I_{sh} = I_L - I_S = I_L - \frac{V_{th} - V_L}{Z_{th}} \quad (13)$$

$$I_{sh} < \eta = I_L < \theta - \frac{V_{th}}{Z_{th}} < (\delta - \beta) + \frac{V_L}{Z_{th}} < \beta \quad (14)$$

Injected power of the DSTATCOM can be expressed as:

$$S_{th} = V_L I_{th}^* \quad (15)$$

It is worth noting that the influence of DSTATCOM in modifying voltage sag is dependent to value of Zth or fault level of the load bus. When the shunt injected current of Ish is maintained in quadrature with VL, the proper voltage modification can be achieved without any active power injection. On the other hand, when the value of Ish is minimized, the same voltage modification is achieved through injecting the minimum apparent power to the system. Voltage sag modification through DSTATCOM compensator is done with the two following methods [118,119].

B.1 Zero active power injection (ZAPI)

In this case, DSTATCOM compensator does not inject any active power to the system. Therefore the entire load active power (PL) should be provided with the Thevenin equivalent of the system. The active power flow through the Thevenin impedance (at load side) can be written as:

$$P_L = \frac{V_{th}V_L}{Z_{th}}\cos(\beta - \delta) - \frac{V_L^2}{Z_{th}} \quad (16)$$

From, eqn. (19) the angle δ is equal to:

$$\delta = \beta - \cos^{-1}(\frac{V_L}{V_{th}}\cos\beta + \frac{Z_{th}P_L}{V_{th}V_L}) \quad (17)$$

$$\delta = \beta - \cos^{-1}(\frac{V_L}{V_{th}}\cos\beta + \frac{Z_{th}P_L}{V_{th}V_L}) \quad (18)$$

For the possible value of δ, the following condition should be satisfied:

$$\frac{V_L}{V_{th}}\cos\beta + \frac{Z_{th}P_L}{V_{th}V_L}) \leq 1 \quad (19)$$

The above constraint can be rewritten as:

$$(V_L\cos\beta + \frac{Z_{th}P_L}{V_L}) \leq V_{th} \quad (20)$$

Thus when the system voltage domain satisfies the (22), then the DSTATCOM compensator can modify the voltage sag without injecting any active power to the system. For such a situation, the current and domain injective power of the DSTATCOM is found by (17) and (18). Note that the injected apparent power includes the reactive component.

B.2 Minimum apparent power injection (MAPI)

As it was noted before, when the injected current domain is minimized, then DSTATCOM can modify the voltage sag by minimum apparent power injecting in to the system. Therefore the condition of injecting minimum apparent power is:

$$\frac{\partial I_{sh}}{\partial \delta} = 0 \quad (21)$$

An analytical description of I_{sh} is obtained from (17) and the solution of (23) provides the following:

$$\delta = \tan^{-1}[\frac{Z_{th}I_L\sin(\beta - \theta)}{V_L + Z_{th}I_L\cos(\beta - \theta)}] \quad (22)$$

Then, for a given load the δ is easily found from eqn. (24). If δ is known, then the current and injected apparent power of DSTATCOM is obtained from (17) and (18) respectively.

VI VOLTAGE SAG DETECTION

Voltage sag detection is an important issue for analysis and mitigation [120]. Several voltage sag detection methods have been proposed [121,122].Those methods are such as peak voltage detection, root mean square (RMS), synchronously rotating reference frame (SRRF) [123], Fourier transform [124], missing voltage technique [125], conventional dq transform [126], Hysteresis Voltage Control technique, Rectified voltage processing method. In paper [127] is propsed a fundamental voltage magnitude detection method which is suitable in both single/three-phase systems for DVR applications in distorted power network

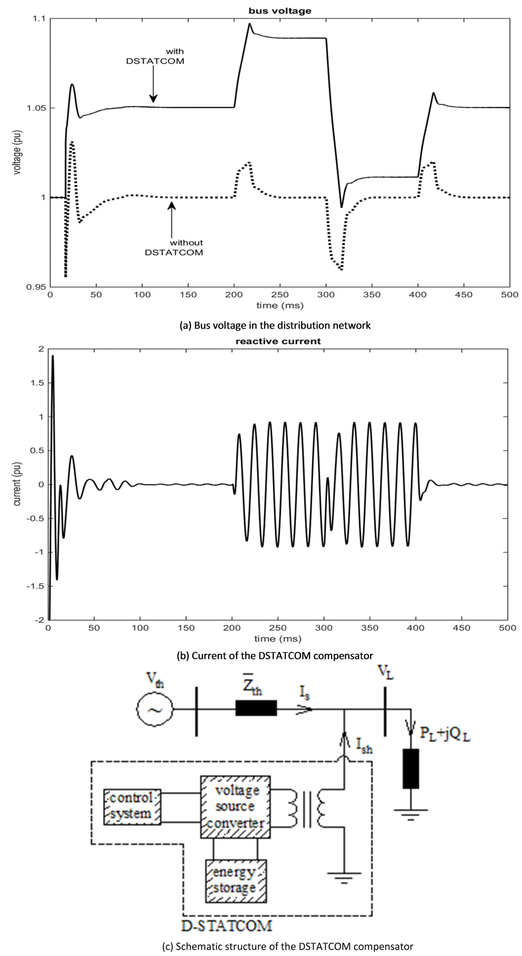


Figure 11: Regulation of bus voltage by DSTACOM

without any low-pass filter. In paper [128] is suggested an adaptive Kalman filter to detect the voltage sag in power system, which the state covariance matrix is changed through the simulation to enhance the Kalman filter in order to detect the amplitude variation of the fundamental component. In paper [129] is used a software phase-locked loop (SPLL) and voltage sag detection algorithm based on least error squares (LES) filter to improve the dynamic response of DVR, in which LES filters have been improved for easy application on the digital system and combined with the improved instantaneous symmetrical components method. In paper [130] is suggested a voltage sag detection methode based on Continuous wavelet transform (CWT) operating even in the presence of flicker and harmonics in source voltage, which the hybrid detection algorithm can detect the start and end times of voltage sag with and without phase jumps 0.5ms and 1.15ms, respectively.

VII CONCLUSIONS

In recent years by granting the power industries to the private sectors and greater demands to this kind of energy the power companies are trying to provide their subscribers with a power with higher power quality to prove their competence. As it was said earlier in this paper, voltage sag has been a common and one of the most important of the power quality problems that has attracted many engineers' attention. Voltage sag is a temporary phenomenon which is mainly created due to short circuit faults, starting big motors and energzation of the transformer. To overcome these temporary phenomenon different strategies were expressed in the following table 2. Using of DVR compensator in new methods can not done the interruption compensation in power systems, any difficulty in the operation of the compensator will be cause the costumers' interruption (due to the series position in the system). But DSTATCOM compensator is able to deliver its stored energy in short time interruption of the network power source. This application of the compensator during the interruption is the same as the UPS operation. For continuous operation of the load, the source should be immediately cut with an electronic switch and operate the compensator like a generator. After resolving the source fault, the compensator is again synchronous with the system and the electronic switch closes. Therefore based on the mentioned advantages regarding applying DSTATCOM compensator than the series compensation, the generally parallel compensator is used to compensate the voltage sag phenomenon.

Table 2: Different strategies for Compensation of voltage sag

Compensation methods	Performance
Conventional methods such as applying capacitor banks, installing new parallel feeders, installing Uninterruptable Power, Supplies proper setting of relays and using current limiting fuses	They are unable to resolve completely power quality problems
New methods (DFACTS) such as DVR and Dstatcom	They can enhance the power quality in power system, but they cannot compensate the interruption event

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