CHAPTER 1
Introduction

1.1 An Overview of Voltage Sag

As the rapid growth of commercial and industrial sectors, the requirement of power electronics applications which used in equipments of those sectors is also plenty. These power electronics applications are voltage-sensitive loads or critical loads, which can be easily interrupted by voltage sags and the resulting losses are significant and the voltage sag is becoming increasingly important.

Among the causes of power quality, the voltage sag (also called voltage dip in the IEC terminology) has been one of the major factors that affect the quality of the power supply that occurs in a power system.

Voltage sag is short duration decrements (between 0.1 pu – 0.9 pu from nominal voltage) in rms voltage amplitude from one-half to several seconds long. Voltage sag is associated with and caused by fault conditions.

Starting a large motor or large load can also result in undervoltages, but these are typically longer in duration than 30 cycles and the associated voltage magnitudes are not as low. Motor starting voltage variations are often referred to "voltage flicker", especially when the motor starting occur frequently.

Utility system faults can occur on the distribution system or on the transmission system. The large majority of faults on a utility system are single line-to-ground faults (SLGF). Three phase faults are more severe, but much less common. SLGF's often result from weather conditions such as lightning strikes, wind and ice. Contamination of insulators, animal contact, and accidents involving construction or transportation activities also cause the faults.

Lightning is the most common cause of faults on overhead transmission and distribution lines. Lightning can cause a fault by directly striking a phase conductor (direct strike) or by striking a grounded object, such as a shield wire or tower (back flash).

As it mentioned above, the voltage sag is one of the major factors that affect the quality of power supply which occurs in a power system, because the voltage sag is more frequent than voltage swells. Several studies report that 92% of all disturbances in electrical power distribution systems are due to voltage sag, transients, and momentary interruptions [1]. Above 1,500 distinct events from "i-grid.com", mostly from large industrial plants located around the U.S. and Canada, were studied and analyzed in detail [2]. The study shows that 63% of the disturbances were single-line-to-ground or single-phase faults, 11% were line-to-line or two-phase faults (when single-phase faults and two-phase faults are asymmetrical faults), and 6% were three-phase or symmetrical faults [3].

The voltage sag has a significant influence on non-electronic loads such as induction motors or AC contactors and especially on voltage sensitive loads i.e., electronic loads such as high-technology equipment related to communication, computers, precise manufacturing equipments, programmable logic controllers (PLC), variable speed drives (VSD), or process control devices, which are all used in modern commercial and industry sectors. These disturbances can cause equipment to fail or shut down, which could result in huge losses to the customers. Many studies have been reported on the loss from an interruption due to voltage sag. In an automotive plant, voltage sag can cost up to U.S. $50,000 per incident [4], in the semiconductor industry it can cost U.S. $30,000 to U.S. $1,000,000 per incident [5] and in a broadcasting facility a half-hour interruption can cost up to U.S. $100,000 in lost income from advertising [6].

1.2 Power Quality Disturbances

The term *power quality* refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system [7]. In recent years, the increasing application of electronic equipment that can cause electromagnetic disturbances or that can be sensitive to these phenomena, has heightened the interest in power quality. The voltage deviations are the most important power quality disturbances happening in the power system [8].

1.2.1 Classification

A general classification and typical characteristics of power system electromagnetic phenomena are shown in Table 1.1[7]. In this table, the detailed descriptions for each power quality variation category are presented. These descriptions provide some history regarding the terms currently in use for each category. From table 1.1, it is possible to make the following remarks regarding voltage disturbances:

1. Transient. Transient or surge is a transient wave of current, potential, or power in an electric circuit. Broadly speaking, transients can be classified into two categories - impulsive and oscillatory. These terms reflect the wave shape of current or voltage transients.

- Impulsive transient is a sudden, non-power frequency change in the steady-state condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative).
- Oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominant frequency), duration, and magnitude. Oscillatory transients can be classified as low, medium, and high frequency transients.

2. Short duration variations are almost always caused by fault conditions, the energization of large loads that require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage rises (swells) or voltage drops (sags), or a complete loss of voltage (interruptions). The disturbances can be classified as:

- Interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min. Interruptions can be the result of power system faults, equipment failures, and control malfunctions. The interruptions are measured by their duration since the voltage magnitude is always less than 10% of the nominal value.

Table 1.1 Categories and typical characteristics of power system electromagnetic phenomena.

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 *m*s rise	50 ns-1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3-50 ms	0-4 pu
1.2.2 Medium frequency	5-500 kHz	20 *m*s	0-8 pu
1.2.3 High frequency	0.5-5 MHz	5 *m*s	0-4 pu
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5-30 cycles	0.1-0.9 pu
2.1.2 Swell		0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles-3 s	< 0.1 pu
2.2.2 Sag		30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell		30 cycles-3 s	1.1-1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s-1 min	< 0.1 pu
2.3.2 Sag		3 s-1 min	0.1-0.9 pu
2.3.3 Swell		3 s-1 min	1.1-1.2 pu
3.0 Long duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8-0.9 pu
3.3 Overvoltages		> 1 min	1.1-1.2 pu
4.0 Voltage imbalance		steady state	0.5-2%
5.0 Waveform distortion			
5.1 DC offset		steady state	0-0.1%
5.2 Harmonics	0-100^{th} H	steady state	0-20%
5.3 Interharmonics	0-6 kHz	steady state	0-2%
5.4 Notching		steady state	
5.5 Noise	broad-band	steady state	0-1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1-7%
7.0 Power frequency variations		< 10 s	

- Sags (dips) is a reduction of voltage magnitude with a duration between a half cycle to a few seconds. Sag durations are subdivided here into three categories – instantaneous, momentary, and temporary – which coincide with the three categories of interruptions and swells. Table 1.1 defines the voltage sag as the reduction in the voltage between 0.1 to 0.9 pu from the nominal voltage.
- Swells is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical magnitudes are between 1.1 and 1.8 pu. Swell magnitude is also described by its remaining voltage.

3. Long duration variations: Long duration variations encompass rms deviations at power frequencies for longer than 1 min. The long duration variations can be classified as:

- Overvoltages are the result of load switching (e.g., switching off a large load), variations in the reactive compensation on the system (e.g., switching on a capacitor bank), or incorrect tap settings on transformers.
- Undervoltages are the result of the events that are the reverse of the events that cause overvoltages. A load switching on, or a capacitor bank switching off, overloaded circuits , can cause an undervoltage.
- Sustained interruptions: The decrease to zero of the supply voltage for a period of time in excess of 1 min is considered a sustained interruption.

1.3 Literature review

Montero-Hernandez and Enjeti [3] proposed a low-cost approach to provide ride-through capability for critical loads. The approach consists of a modified ac/dc/ac converter (based on boost converter) and static transfer switches (STSs). Under normal operating conditions, the load is connected to the utility supply via the main static transfer switch. However, in the event of voltage sag, the main static transfer switch is turned off, and the auxiliary static transfer switch is turned on, thereby transferring the load to the inverter supply with seamless transfer. The advantages of this proposed system are not using of special energy storage device and bulk magnetic device (power transformer), low cost, and reduced size.

Li, *et al*. [9] presented the investigation and improvement of transient response of a dynamic voltage restorer (DVR) at medium voltage level. A DVR is proposed for use in the medium-voltage or low-voltage distribution network to protect consumers from sudden sags in grid voltages. The proposed method is the damping of the transient LC oscillations initiated at the start and the recovery instant from voltage sag. These high-frequency oscillations are caused by LC filter at the primary of the injected transformer. Possible control schemes and their effects on the oscillation attenuation are also studied. Subsequently, an effective and simple resonance damping method is proposed by employing a closed-loop control with an embedded two-step Posicast controller. It is shown that the proposed damping methods improve both the transient and steady-state performance of the DVR.

Subramanian and Mishra [10] presented the interphase ac-ac topology for voltage sag supporter. The AC-AC choppers and injected transformers are used in this topology, the support of the voltage sag in a phase is drawn from the other phases, i.e. the input power for a voltage sag supporter for one phase is taken from the other two phases. The advantages of this proposed system are absence of any storage device, low cost, small size, low maintenance, no limitation on the real power injection and ride-through capability, ability to compensate 0% - 100% single-phase sag, 50% three-phase balanced sag, and ability to compensate the phase jumps. However this topology has the disadvantages as the voltage harmonics cannot be compensated (due to AC-AC converter), the PCC (point of common coupling) may experience noise due to AC chopper, and required power is dawn from faulty phases in the case of three-phase balanced sag.

Aeloiza, *et al*. [11] proposed a new voltage sag compensator for critical loads in electrical power distribution systems. The proposed scheme employs a pulse width-modulation ac–ac converter (four insulated gate bipolar transistors per phase) along with an autotransformer. During a disturbance such as voltage sag, the proposed scheme supplies the missing voltage and helps in maintaining rated voltage at the terminals of the critical load. These proposed systems have the advantages which are not using of energy storage components, fast response, low cost, low loss. The disadvantage is employing the auto transformer.

Tumay, *et al*. [12] presented sequence reference frame-based new sag/swell detection method for static transfer switch. In the proposed method, the positive sequenced–q components are passed through a differentiator. The resulting values are then summed with the positive sequenced–q components and calculated to extract the original positive sequence components. The obtained original positive sequenced component is used as an ideal error signal to generate the transfer signal. This improves the response time of sag/swell detection when compared to conventional methods because 100-Hz ripple is eliminated, and the transfer signal is obtained with less delay. The simulation results show that the delay times of the proposed method are 0.16 – 0.28 ms compared to 3.04 – 10.32 ms of the conventional method.

Cheng, *et al*. [13] presented sag compensator using new synchronous reference frame (SRF)-based sag detection to avoid transient effect (voltage spike) under practical utility conditions at Hsinchu Science-based Industrial Park (HSIP) TAIWAN. This proposed system is designed to avoid the false triggering of the compensator caused by transient spike voltages that come with switching of power-factor-correction capacitors, switching of circuit breakers, or lightning strikes by employing disturbance filter at the controller.

Bae, *et al*. [14] proposed a line-interactive single-phase dynamic voltage restorer (DVR) with a novel sag detection algorithm. The proposed detection algorithm has a hybrid structure composed of an instantaneous detection part and the root-mean-square (rms) variation detection part. When instantaneous sag is detected, the rms variation detector is selected to calculate the rms variation. The real sag is judged if the rms value is decreased. This method is suitable for distorted input voltage detection. The line-interactive DVR with the proposed algorithm can compensate the input voltage sag or interruption within 2.0-ms delay.

Gregory, *et al*. [15] presented the static transfer switch operational considerations**.** The basic operation of static transfer switch is described in this paper since little has been published in the public domain on its detailed operating characteristics. This paper addresses this deficit and in addition describes a computationally efficient detection algorithm for power quality disturbances (sags).

Mokhtari and Iravani [16] presented the effect of source phase difference on static transfer switch performance. This paper investigates the impact of phase difference between the corresponding voltages of the two sources on the load transfer performance achieved by a STS. The studies indicate that the impact of phase difference on the STS load transfer time is insignificant when the sensitive load is a passive (e.g., RL) load. However, if the load can operate in a regenerative mode (e.g., a motor load), the effect of phase difference on the transfer time is noticeable. The studies show that a phase difference of 25° can increase the load transfer time by about 2 ms.

1.4 Scope of This Thesis

The main objectives of this thesis are to design and develop simulation model of the vector control system for voltage sag compensator using back-to-back converters and to design and implement the vector control system for voltage sag compensator using back-to-back converters.

1.5 Outline of This Thesis

The aim of this thesis is to design and develop the vector control system for voltage sag compensator using back-to-back converters.

In this thesis, the paper is organized into five chapters as follows:

Chapter 2 voltage sag compensations. The current technologies in voltage sag compensations are described in this chapter.

Chapter 3 voltage sag detections. In this chapter, the voltage sag detections are mentioned. The proposed voltage sag detection is analyzed and implemented. The experimentation is established to investigate the performance of the proposed voltage sag detection. This experimentation is performed with several conditions to certify the simulation results.

Chapter 4 static transfer switch. The operation detail of static transfer switch is explained in this chapter. The analysis and simulation of static transfer switch operations are done with various cases such as load types and point-on-wave initiation of voltage sag.

Chapter 5 proposed voltage sag compensator using back-to-back converter. With the incorporation of proposed voltage sag detection, static transfer switch, and back-to-back converters, the proposed voltage compensator is analyzed and implemented. The model of proposed system is constructed and improved by using of computer simulation software. The model validation is done by experimentation in various conditions.

Finally, chapter 6 provides the conclusions and some suggestions for future research on this subject.