CHAPTER 1
Introduction

1.1 Background and Motivation

Voltage sags are the most prevalent disturbances in electrical power systems; a recent survey attributes them to 92% of all disturbances [1]. Most electronic loads are sensitive to voltage variations, which can lower their performance or even shut down the process that they control. With the increased use of large converter-based loads in industry, computers for office automation, and other sensitive electronic circuitry, electric power quality has become an important issue. Special attention has focused on critical loads, such as medical centers, automobile manufacturing plants, semiconductor industry, broadcasting facilities, and commercial buildings. In all of these cases, numerous electronic loads are sensitive to voltage sags and disturbances. Although the exact cost of poor power quality cannot be known with certainty, it is estimated that voltage sag disturbances cost millions of baht every year in Thailand.

Voltage sag in electrical system will cause electrical equipments malfunction or fail. The main reasons are:

1) The voltage regulator converts the non-regulated DC voltage to a regulated DC voltage. If the AC voltage drops, the voltage on the DC side of the rectifier drops. The voltage regulator is able to keep its output voltage constant over a certain range of input voltage. If the voltage at the DC bus becomes too low, the regulated dc voltage will also start to drop. Ultimately errors will occur in the digital electronics.

2) A trip in an under-voltage detector circuit. Normally an under-voltage detector circuit is used to check whether the voltage level is enough to supply load. Sometimes, it is difficult to specific which level of voltage will be enough to make the equipment work accurately. For example a voltage level at 70% is enough to supply half load. When a voltage sag occurs at 70% the equipment should be run as normal. With under-voltage detector circuit, the system will be shut down.

3) A trip of unbalance relay. In a 3 phase electrical system, if a voltage sag occurs, usually it happens in one or two phases called asymmetrical. This will cause an unbalance voltage level. A motor or a transformer may get high temperature and breakdown. Usually most of electrical equipments are equipped with the unbalance relay to protect this problem. If the unbalance level is higher than the set limit, the system will be shut down. The problem is if we set 2-3% unbalance limit, and the voltage sag occur temporary 20-50% for1-2 second , the system will be shut down. Even though this 20-50% in 1-2 second cannot make any damage to motors or transformers.

A fault in a transmission line, e.g. 230 kV, may cause a voltage sag which may impact a sensitive equipment located hundreds kilometers away. Fault in distribution system is different from fault in transmission line. This is because impedance from a step down transformer and a radial configuration cause fault only among users who share the same transformer. The electrical users in the feeder where fault happens will observe a voltage sag followed by the systems shut down. While the users in the other feeder will observe a voltage sag till the fault fades.

To solve the voltage sag problem, mostly a DVR (Dynamic Voltage Restorer) which includes 3-phase, 4-wire, 4-leg inverter [2], [3] or 3-phase, 4-wire, 3-leg inverter (split-capacitor)[4],[5] is used to inject voltage to the transformer which series connected to compensate the voltage level that is missing during the voltage sag. To control both kinds of inverters, 3D SVM(Three Dimension Space Vector Modulation) technique was used. This technique transforms the reference voltage into the $\alpha\beta 0$ frame. The disadvantage of the DVR technique is the calculation time consuming in transforming voltage from *abc* frame to $\alpha\beta 0$, then from $\alpha\beta 0$ to *abc* again.

The objective of this research is to present the solution of the voltage sag for a critical load by using inexpensive power electronic devices and an inverter without large capacitor, also to present an inverter control algorithm which provides a fast calculation and response to the voltage sag.

1.2 Literature Review

Prasad, *et al.* [3] presented space vector modulation schemes analyzed for a four-leg voltage source inverter. The analysis is performed with respect to switching losses and total harmonic distortion under both balanced and unbalanced load conditions over the entire range of modulation index values and over varying load power factor angle.

Zhan, *et al.* [4] presented a dynamic voltage restorer (DVR) based on the voltage-space-vector pulsewidth-modulation algorithm. Phase-jump compensation is achieved using a software phase-locked loop and a lead-acid battery energy store. A battery-charging control technique using the DVR itself is also described. To validate the control of the DVR, a three-phase prototype with a power rating of 10 kVA has been successfully developed.

Zhan, *et al.* [5] presented the modified voltage space vector pulse-width modulated (PWM) algorithm for a four-wire dynamic voltage restorer (DVR). The switching strategy based on a three-dimensional (3-D) $\alpha\beta 0$ voltage space is applicable to the control of three-phase four-wire inverter system such as the split-capacitor PWM inverter and the four-leg PWM inverter. In contrast to the conventional voltage space vector PWM method, it controls positive, negative and zero sequence components of the terminal voltages instantaneously. Three 3-D modulation schemes are analyzed with respect to total harmonic distortion (THD), weighted total harmonic distortion (WTHD), neutral line ripple and switching loss over the whole range of the modulation index when the DVR experiences both balanced and unbalanced sags with phase angle jumps.

Reed, *et al.* [6] presented a novel switching device using a hybrid system of a parallel switch and a thyristor switch, and the application of this switching device to Solid State Transfer Switch (SSTS) system. Development efforts of advanced static compensation technology at the distribution level have resulted in a new Compact Distribution Level Static Compensator (D-STATCOM) device which exhibits high speed control of reactive power compensation in order to provide voltage stabilization, flicker suppression, and other types of system control.

Schoenung, *et al.* [7] presented small Superconducting magnetic energy storage (SMES) technology and cost reduction estimates. SMES has been under development for electrical system applications for sometimes. Large units $(\geq 10\,\mathrm{MWh})$ have been designed for electric load management. Small systems $(< 10\,\mathrm{MWh})$ have been designed for power quality enhancements. Small systems, in particular, can provide momentary carry over on a distribution network, thus avoiding outages in customers electric supply. The price of today's small units is relatively expensive. The objective of this study was to evaluate possible cost reductions of small SMES devices to determine long-term feasibility for use in utility's systems.

Windhorn [8] presented UPS system that employs a rotary converter (motor-generator set) as a post conditioner for a simple rugged inverter that can operate either from rectified utility power of batteries to provide regulated sinusoidal power with good transient capacity, low distortion, and complete isolation of the load from the utility is described.

Samineni, *et al.* [9] presented the modeling and analysis of a flywheel energy storage system for voltage sag correction. A flywheel stores energy in the form of kinetic energy. The amount of energy stored varies linearly with the moment of inertia of the flywheel, and the square of its angular velocity. Flywheels can be designed for low speed or high speed operation. A low-speed flywheel has advantages of lower cost and the use of proven technologies, when compared to a high-speed flywheel system. The main disadvantages are less stored energy per volume, higher losses and increased volume and mass.

Jouanne, *et al.* [10] presented the energy storage for Adjustable-Speed Drives (ASD). Fuel cell provides continuous power through the consumption of hydrocarbon fuel, typically, natural gas. Thus, the operation is more similar to a battery, in the electrochemical rather than electromechanical conversion. A fuel cell could be interfaced with the AC line of a power distribution system. However, it would be more appropriate to operate the fuel cell at all times, because the expense is much greater than an M-G set and it cannot be quick started from cold standby. They are reliable and efficient, with little maintenance and few mechanically moving parts, but they cannot respond rapidly to load changes, and the high cost hardware.

Manuel, *et al.*[11] presented the four-leg inverters have which been selected as one of the preferred power converter topologies for applications that require a precise control of neutral current, like active filters. The main advantage of this topology lies in an extended range for the zero sequence voltages and currents. However, the addition of the fourth leg extends the space vectors from two to three dimensions, making the selection of the modulation vectors more complex. Most of the algorithms that deal with this problem require an $\alpha\beta\gamma$ transformation. The paper presents a new space vector modulation algorithm using *abc* coordinates (the phase voltages) avoiding the $\alpha\beta\gamma$ transformation. Thanks to the use of *abc* coordinates, the algorithm is much simpler and more intuitive than in $\alpha\beta\gamma$ representation, drastically reducing the complexity of modulation algorithm and the computational load associated to it.

Rui Wu, *et al.*[12] presented the principle of the SVM in *abc* coordinates in detail. The traditional SVM require a bit of digital logic and computational power to determining the duty ratio of each switch. However, the algorithm for three-phase four-leg inverter in *abc* coordinates avoids the $\alpha\beta\gamma$ transformation, which can make the selection of the switching vectors and calculation of the duty cycle much easier, and reduce the complexity of the modulation obviously. The implementation on a field programmable gate array (FPGA) of the SVM algorithm is also studied. The inverter implemented on FPGA has a fast response and high performances because FPGA can execute several processes synchronously in stead of executing instructions step by step.

1.3 Purposes of the Study

1.3.1 To design and prototype construction of 3-phase, 4-wire voltage sag compensator for critical load.

1.3.2 To improve the neutral current under voltage sag and nonlinear load condition.

1.3.3 To develop a control method for 3-phase, 4-wire, 4-leg inverter with 3D SVM based on *abc* coordinates.

1.4 Education/Application Advantage

1.4.1 A voltage sag compensator prototype for critical load is obtained.

1.4.2 An efficient and quick response algorithm to control 3-phase, 4-wire, 4-leg inverter is obtained.

1.5 Research Scope

1.5.1 Design, Construct and test voltage sag detector.

1.5.2 Design, Construct and test voltage boost circuit.

1.5.3 Design, Construct and test 3-phase, 4-wire, 4-leg inverter.

1.5.4 Develop control algorithm for voltage sag compensator by control

3-phase, 4-wire, 4-leg 3kVA voltage 380 V inverter with 3D SVM based on *abc* coordinate.

1.6 Research Methodologies

1.6.1 Study 3-phase, 4-wire voltage sag compensator topology.

1.6.2 Study/design/construct/test voltage sag detector.

1.6.3 Study/design/construct/test voltage boost circuit.

1.6.4 Study/design/construct/test 3-phase, 4-wire, 4-leg inverter.

1.6.5 Develop control algorithm for voltage sag compensator by control 3-phase, 4-wire, 4-leg inverter with 3D SVM base on *abc* coordinate.

1.6.6 Test over all system.

1.7 Research Contributions

The main contributions of this research include the following:

- The definition of voltage sag is proposed in Chapter 2 of this thesis. The European norm EN 50160 (2000-01-24) and IEEE. Std. 1159-1995 Standard is proposed. The cause of voltage sag and classification of voltage sag and effect of voltage to sensitive load, IT and Process Control, Contactor and Asynchronous Motors etc.
- The voltage sag mitigation method, solutions using energy storage devices and solutions no using energy storage devices are presented in Chapter 3. The summarize the characteristics of most of the systems described in table 3.1 and table 3.2.
- Chapter 4 presents the voltage sag compensator that does not require energy storage devices to provide compensation or mitigation for voltage sags. This hardware consists of voltage sag detector, dc/dc converter, solid state transfer switch, 4-leg inverter. The advance of 4-leg inverter and algorithm lie in and extended range for the zero sequence voltage and currents. The space vector modulation algorithm use of *abc* coordinates is mucht simpler

and more intuitive than in $\alpha\beta\gamma$ representation, reducing the complexity of modulation algorithm and the computational load associated to it.

1.8 Thesis Organization

This thesis is organized into six chapters including this chapter. Chapter 2 reviews the voltage sags definition, cause of voltage sags, voltage sags type. The effect of voltage sags to the sensitive load are also described. Then, the voltage sags mitigation method is explained in Chapter 3. The way to classify the equipment providing rid-through for electric loads in by considering the use of some kind of energy storage device. Chapter 4 presents the main results of this thesis, the 3-phase 4-wire 4-leg voltage sags compensator based on 3 dimensions space vector modulation in *abc* coordinates. This Chapter 4 presents the voltage sag compensator that which does not require energy storage devices to provide compensation. The system can handle the neutral current under unbalanced voltage sags, unbalanced load and nonlinear load conditions. The main components of the system consists of 4-leg inverter topology and algorithm use of *abc* coordinates is much simpler and more intuitive than in $\alpha\beta\gamma$. With use of algorithm on *abc* coordinates, it reduces the complexity of modulation algorithm and associated computational load. In Chapter 5, the simulation and experimental results are presented. Finally, conclusions and recommendations for future studies are given in Chapter 6.