Chapter 1

Overvoltage Surges and their Effects

1.1 Introduction

Power equipment are often exposed to short duration impulse voltages of high amplitude produced by lightning or switching transients. These overvoltages may deteriorate or permanently damage the insulation system of power equipment. Efficiency of entire electrical network depends on the reliability of insulation system of power equipment. Hence, determining the insulation integrity of equipment against transient surges is essential for insulation coordination, reliability of individual power equipment and the power systems as a whole.

Impulse voltage test is generally done in laboratories according to international standard IEC 60071-1, Insulation co-ordination – Part 1: Definitions, principles and rules, 2006 [1]. During impulse withstand voltage tests, it is sometimes difficult to generate the standard impulse waveforms on large equipment of the ultra high voltage (UHV) class due to low inductances and also due to the limited capacity of the generator including the power supply [2, 3]. As a result, the test equipment are subjected to unidirectional or bi-directional or both types of non-standard oscillatory impulse waveforms. Also, in practice, the transient overvoltages caused by lightning as well as by switching consist of wide varieties of wave shapes, ranging over broad spectrum of frequencies. These transient overvoltages do not always resemble the standard lightning and switching impulse wave shape [4]. Hence, it is necessary to assess the effects of standard as well as non-standard lightning and switching impulse waveforms that represent actual surge waveforms in the field on power equipment and determine the probability of insulation breakdown due to such stresses.

1.2 Transient Overvoltages in Power Systems

The IEEE Std C62.82.1-2010 [5] defines overvoltage as “the phase to ground or phase to phase voltage with crest value exceeding the corresponding crest of the maximum system voltage”. The transient overvoltages can be classified into various ways depending on their origin, amplitude, or frequency spectrum. Based on the origin of the transients, they originate from a lightning stroke, some internal faults within the system or by the switching operations [6]. Electromagnetic and Electromechanical transients are another type of classification done
based on their origin [7]. Based on their occurrence, lightning overvoltages are classified as direct strokes and induced strokes. The direct strokes generally have a high rate of voltage rise (1000-10,000 kV/μs) and high peak current values (1-200 kA) [6]. A direct lightning stroke to a line has the potential to permanently damage line insulators and terminal equipment [6]. Induced strokes are caused by nearby strokes to ground or between clouds, direct strokes to phase conductors, direct strokes to towers or direct strokes to earth wire. The induced lightning surge voltage consists of two superimposed components: (i) a travelling wave and (ii) an electro-statically induced voltage. Induced strokes produce lower overvoltages 20-100 kV and discharge current around 2 kA or less [8]. According to the International Electrotechnical Commission (IEC) [9], based on wave shapes, transient are grouped into “oscillatory transients” and “impulsive transients”. Oscillatory transients have bi-directional polarity and are primarily caused by switching operations, ferro-resonance etc.. Impulsive transients have unidirectional polarity and are caused mainly by lightning stokes. Based on time duration, overvoltages are classified as Lightning (0.1μs-1ms), Switching (10 μs to less than a second), Sub synchronous Resonance (0.1 ms-5s), Transient Stability (1 ms-10s), Dynamic Stability, long term dynamics (0.5-1000s), Tie line regulation (10-1000s), and Daily load management, operator actions (Up to 24h) [7, 10]. In addition to it, overvoltages can also be classified into four main categories based on frequency range: very fast front (100 kHz to 50 MHz), fast front (10 kHz to 3 MHz), slow front (50/60 Hz to 20 kHz) and temporary overvoltages (0.1 to 1 kHz) [11].

The main operations that can produce switching overvoltages are line energisation and de-energisation, capacitor and reactor switching, occurrences of faults and breaker openings etc. Switching overvoltages is of longer duration than lightning overvoltages. Compared to lightning overvoltage, switching overvoltage rise is less steep and it’s magnitude and wave shape depends on system voltage and impedance [12]. Switching transients usually show complex waveforms with frequencies in the range of 100 Hz to 1000 Hz superimposed on the power frequency. They belong to the category of slow front transients. The total amplitude of the overvoltage due to switching consists of a transient component superimposed on a power frequency component [13].

Electrical transients are mathematically represented by a hyperbolic partial differential equation. In 1750, D’Alembert solved the partial differential equation for a vibrating string
With the advent of digital computers, various approaches of solving a transient, like the travelling wave theory, lumped parameter circuit theory, basic theory of grounding etc. were established. The Schnyder-Bergeron method, and the Bewley lattice diagram method and the transient network analyser (TNA) were the popular methods for calculating electrical transients [14]. A lot of research has been done on the classification and analysis of transients of various power system phenomena that involves various kinds of computational techniques such as Fourier transform, wavelet transform, wavelet network, SVM tools etc. The computational method should be capable of representing equally well, lumped and distributed parameters over a wide frequency range and include nonlinearities [14]. The Fourier frequency domain method has the advantages of providing high accuracy and improving the computational efficiency for transient calculations. The Z-transform method applied to the transient analysis of power systems first converts the frequency domain to the Z-domain and then directly to the time domain. The EMTP is a general-purpose computer program for simulating fast transient effects in electric power systems and has been considered as a standard simulation tool. More recently, numerical electromagnetic analysis (NEA) is becoming another powerful approach especially to solve three-dimensional transient and a non transverse electromagnetic (TEM) mode transient. The NEA calculates Maxwell’s equation directly from the geometrical and physical parameters of a given system. Two most important and widely used methods of NEA are the method of moments (MoM) in the frequency and time domains and the finite-difference time-domain (FDTD) method [14]. The Disruptive Effect Method (equal area criterion) is used as a universal model to predict the insulation strength under nonstandard impulse voltages. The Unconditionally Sequential Approach is used to predict the insulation strength under bi-directionally oscillating impulse waves [15].

1.3 Impulse Behaviour of Power Equipment
During transient phenomenon, the power equipment are subjected to high frequency overvoltages for very short duration of time. Also, they are excited with high current and voltage peaks compared to their normal rating. The voltage which a particular insulating component can withstand depends upon the magnitude of the stress, the rate at which it is applied and the duration of the stress [16]. In other words, the severity of insulation degradation depends on several factors corresponding to the voltage waveform like the steepness of the wave, instant of chopping, time to collapse, frequency of oscillations,
overshoot near the peak etc. Knowledge of magnitude, duration, wave shape, polarity and frequency spectrum of the incident voltage wave is very important to reduce insulation failure and maintain maximum reliability in power systems [4].

Several important investigations and their results have been published on voltage stresses due to impulse waveforms on power equipment. The present section reviews the response against overvoltages due to lightning, and switching overvoltages on three most important power equipment in power systems namely power transformers, insulated cables and surge arresters.

### 1.3.1 Power Transformers

In 1915, Wagner [17] investigated surge phenomena and reported that dielectric material in transformer fail due to lightning waveforms and switching operations. The significance of chopped impulse application and repeated exposure to impulses during impulse testing of power equipment was studied in [17, 18]. Aschlimann [19] and Sirotinski [20] showed that voltage stresses due to chopped waveforms were higher than those due to full wave of the same steepness. Heller and Veverka [21] also observed higher inter-turn and inter-disc insulation stresses for chopped waves. Mitra et al. [22] studied winding response of transformer to oscillatory voltages. They reported that the effect of oscillatory voltages were worse than under full lightning impulse, chopped lightning impulse or steep front long tailed switching surge. Venkatesan and Usa [23] studied the impulse strength of air, transformer oil, and oil impregnated paper (OIP) insulation under both unidirectional and bidirectional non-standard impulses. They determined the insulation strength of power transformer under unidirectional and non-oscillatory, and bidirectional oscillatory waves using disruptive effect (DE) method and unconditionally sequential method respectively. They observed that positive and negative polarity of oscillating waveforms affects the insulation breakdown in power equipment and the effects of chopped and oscillatory impulses were critical compared to full standard impulse wave. Okabe et al. [24] performed several studies on insulation characteristics of high voltage (HV) and ultra-high voltage (UHV) power equipment under non-standard impulse waves. Important results from their studies on transformer insulation are listed below:

1) The breakdown voltages of oil gap insulation under typical non-standard waveforms like: sharp rise-short tail impulse, damping oscillatory unipolar impulse voltages, and oscillatory voltage waveforms with peak value higher in the second wave than in the first wave were higher than standard lightning impulse voltages [25].
2) The dielectric breakdown and the partial discharge inception voltage values of oil gap, turn-to-turn and section-to-section insulation of oil immersed power transformer under single pulsed non-standard impulse waveform, waveform with a pulse in the crest and a subsequent flat section, damped oscillation waveform and rising oscillation waveforms were always higher than those under standard lightning impulse waveforms [26, 27].

3) In actual field, the time to peak value of switching impulse varied from 100 μs to 1000 μs. Peak value of impulse waveform had negligible influence on the insulation characteristics of UHV power equipment. It was suggested to retain switching impulse test waveform of 250/2500 μs for UHV equipment similar to the equipment of 800 kV or less [24].

4) Transformers in UHV station were subjected to maximum overvoltage due to direct lightning stroke. The effect of maximum overvoltage on core-type transformers was different from that on shell-type transformers [28].

5) The back-flashover surge waveforms have steep front and short duration and direct lightning strikes had gradual initial rise and a long duration. This change in wave shape had harsh impact on equipment insulation system [29].

6) Investigation of insulation characteristics for a standard and non-standard lightning impulse waveform in the SF₆ gas gap showed that the insulation requirements of non-standard impulse waveforms were less severe compared to standard waveforms [30].

Fast transient overvoltage (VFO) and very fast transient overvoltage (VFTO) occur due to switching operations in gas insulated switchgear (GIS) or earth faults. Y. Shibuya [31] and Popov et al. [32] demonstrated that VFTO increases the inter-turn voltages of the transformer winding finally leading to insulation breakdown. Vandermaar et al. [33] studied insulation characteristic of oil-paper insulation under steep front impulse voltage. They observed that 50% breakdown probability voltage under steep front impulses were lower than for full lightning and switching impulses and might fail at voltages below the lightning impulse design level. The multiple impulse breakdown results showed that oil-paper insulation breakdown strength could be lower than 100 kV/mm. The breakdown process at rise times below 50 ns was different from the breakdown process at rise times above 50 ns.

Overhead line-transformer and cable-transformer interfaces can also impose oscillatory switching overvoltages in the transformer and lead to insulation failure [34-36]. These
oscillating switching overvoltage surges can excite the internal resonances and produce very high voltage internal stresses in transformers. Indulkar [35] studied the distribution of transient voltages at different points of line-transformer and cable-transformer interfaces and reported that the severity of switching overvoltages depends on the type of neutral connection of the transformer. When the primary and secondary connections were similar, the input and output waveforms were similar except with reduced peak values in the output side. Overhead line or cable connected to the transformer reduces the peak overvoltages in the transformer. Gustavsen [36] analyzed the resonant overvoltages caused by cable-transformer interaction. He identified four possible situations leading to high overvoltages on unloaded low voltage side of the transformer namely ground fault initiation at the cable end, energisation from a bus bar which is connected to several other cables, cable energized from another cable of equal length, and capacitor bank energization at the far end of the feeder cable. In another important research work, Zhou and Boggs [37] studied the effect of high frequency cable attenuation on transformer response to lightning overvoltages and reported that severity of effect of overvoltage depend on type and length of cable, arrester lead length and rise time of lightning wave. They also reported that high frequency attenuating cables were more effective in protecting the transformer from the effects of lightning surges.

1.3.2 Cables

Cables are affected by various overvoltage surges coming from the overhead lines. A cable connected to high-voltage side of an unloaded transformer can produce very high overvoltages on the low-voltage side due to resonance phenomenon [36]. Studies on transient disturbances on transmission system have shown that lightning and switching operations are followed by a travelling wave of a steep wave front which is responsible for damaging insulation system in power equipment. Therefore, transient overvoltages must be taken into account when designing the insulation system of a cable. The first transient voltage analysis was performed by Lord Kelvin to investigate the wave propagation characteristic on the planned Trans-Atlantic telecommunication cable in 1854 [14]. Switching surges were considered a concern when high voltage and long transmission lines and networks became popular. Symmetrical component theory was developed in 1918 to analyze the switching surges [14]. Rusek and Uhlmann [38] calculated maximum sheath voltage along a semi-infinite cable against a step voltage between the core and the sheath. Wedepohl, et al. [39] also investigated the sheath overvoltages in cables and reported that Rusek and Uhlmann
formula [38] assigned high values while calculating maximum sheath overvoltages. Investigations of Gustavsen, et al. [40] also supported the observations of Wedepohl, et al. [39].

Several works have been done to evaluate the effects of the semiconducting screens, the conductors, and the surrounding earth on the propagation constants of electromagnetic waves in concentric underground power cables. Gustavsen, et al. [40] investigated transient sheath overvoltages in submarine cables with insulating and semi-conductive interlayer. They found that sheath-armour bondings or semi-conductive sheath-armour interlayer in armoured cables limit the sheath overvoltages. When a cable of finite length is subjected to step voltage, the maximum sheath voltage is affected by the sheath grounding at the near end. The semi conducting layer reduces the maximum sheath voltage along the cable. Baba et al. [41] analyzed the transient response of a power cable using finite difference time domain (FDTD) method. They reported that propagation velocity of a surge current depends on the conductivity of the cable layers. The effect of semi conducting layer on wave propagation and transient characteristics was investigated by Ametani et al. [42]. They reported that semi conducting layer in the cable produced more attenuation and longer oscillations in voltage waveform. The propagation velocity and the characteristic impedance of the coaxial propagation mode were found to be lower in presence of semiconducting layer. The sheath over-voltage was higher on a cross-bonded cable compared to non-cross bonded cables [43, 44]. Goto et al. [44] investigated the surge propagation on overhead, underground and submarine cables. They observed that coaxial mode of surge propagation in cables was independent of surrounding medium but earth return mode depended on the surrounding medium. Martinez and Molina [45] investigated the surge protection of underground distribution cables. They observed that overvoltages generated along the cable could be reduced by using large number of arresters. Henriksen et al. [46] analyzed lightning overvoltages in a cable which is inserted in an overhead line and protected by surge arresters at both ends. Calculations were done based on the forward and backward travelling voltage waves at the cable ends. Greenfield [47] studied the transient behaviour of short and long cables. The long cable was found to be self-protective against transients. The transient waveform crest can reach nearly 3 times in short and about 1.6 times its entering value in long cable.
1.3.3 Surge Arresters

Surge arresters provide the primary protection against different types of lightning or switching overvoltages. They are designed to have an extremely high resistance during normal system operation and a relatively low resistance during transient overvoltages. They are connected in parallel with the equipment to be protected. When overvoltages exceed the surge arrester voltage operating level, the arrester allows the current to pass through it until the overvoltage is reduced below its protective level [48]. The duration of arrester current flow depends on overvoltage duration [12, 49].

The surge arrester failure studies include mainly the desired lightning performance and calculation of energy stresses on arresters. Arrester failures are generally attributed by high voltage stresses caused by high earth resistance of the grid grounding system, sealing defects and environmental contamination, resonance and switching and lightning overvoltages, repeated transients of long duration and large magnitude [50, 51]. Peak value of voltage that appears between the terminals of an arrester during the passage of discharge current is known as residual voltage [52]. The protection level of surge arrester is determined by the maximum residual voltage [53]. High voltage metal-oxide surge arresters are stressed mostly by the switching overvoltages and medium-voltage surge arresters are stressed mostly by the direct lightning overvoltages. There are standard methods for determining the energy absorption capability for high voltage metal oxide surge arresters but for the medium voltage surge arresters, the energy absorption capability is determined by analytical methods [24]. IEEE working group 3.4.11 [54] reported that that metal oxide arresters have dynamic characteristics that are significant for studies involving lightning and other fast-front surges. The dynamic characteristics become prominent for current waves with peak in the range of 8 µs or more. When the time-to-crest of arrester discharge currents were shorter than 4 µs, voltage spikes appeared on the front of the residual voltage waveform. The residual voltage for a given discharge current increased by approximately 6% as the time to crest of the current was reduced from 8 µs to 1.3 µs [54]. The residual voltage depends on the discharge current and its wave shape parameters like rates-of-rise, rise times, decay times etc. The dynamic characteristics of arrester was analysed for current surges with different front times ranging from microsecond to nanosecond using electromagnetic transient program (EMTP) [55]. When the surge arrester was subjected to discharge current waveforms having front times in microseconds, the peak of the residual voltage wave occurred before the peak of the
current wave. But for discharge current waveform with front time in nanosecond range, the peak of the residual voltage wave occurred after the peak of the current wave. Impulse current with front time of 1 µs produced 8-12 % higher residual voltage than an impulse current with front time of 8 µs. And impulse current with front time of 8 µs produced 2-4 % higher residual voltage than an impulse current with front time of 45-60 µs [56]. Most lightning ground flashes consist of multiple return strokes. These can impose stresses of exceptional severity on the arresters. The effect of return stroke current parameter on the arrester energy is reported in [57]. They reported that arrester energies are mostly sensitive to the tail time of the return stroke current compared to rise time. The computation based on the lightning limiting parameters method of the surge arrester minimum energy absorption capability is presented in [24]. They observed that the effect of lightning current wave duration is very small on failure rates of surge arresters when energy absorption capability is less than 20 kJ/kV.

Darveniza et al. [58] investigated the effects of multiple pulse lightning currents on metal oxide surge arresters and showed that the damage caused is not normally evident with standard lightning current tests. The first stroke of lightning flash is assumed to be the strongest to inject the highest amount of energy into the surge arrester. [24] has proposed to model multiple flashes by an equivalent single triangular current wave with the linear rising front and linear tail decay. Kim et al. [59] measured the response of arrester block to steep front impulse current: 1/2 µs, 4/10 µs and 8/20 µs impulse current. They concluded that the steep front impulse study is very important for insulation coordination. The failure probability for gapless metal oxide arresters depends on its energy capability, the rated voltage, and the system configuration [60]. Also, the behaviour of surge arresters varies for various surge waveforms, depending on the peak and the slope of the overvoltage [61]. Different non-destructive and destructive diagnostic techniques to assess the condition of a metal oxide surge arrester when subjected to severe lightning strikes in the field were presented in [62]. The dynamic effects of surge arrester are significant considerations for deciding proper arrester location and insulation coordination studies.
From the review, few important points with regard to transient analysis are summarised as follows.

1. Investigation of the voltage stresses in the insulation system of power equipment is essential for minimization of insulation failures and maintaining high reliability of the equipment.

2. Lightning overvoltages are different from switching overvoltages. Lightning overvoltages are characterised by fast front, unidirectional and of very short duration voltages produced by lightning. Switching overvoltages are characterised by slow front, unidirectional, highly damped oscillatory and of short duration voltage generated usually by switching or faults [5].

3. Transient surges contain high frequency overvoltages ranging from several kilo Hertz to several mega Hertz and hence it is essential to consider high frequencies in modelling network components for transient analysis [63].

4. Different stress conditions are aroused in the insulation systems by different wave shapes. Therefore, it is important to analyse a large number of waveforms including standard as well as non-standard impulse waveforms which comply with the actual transient surges, to determine the probability of insulation breakdown in power equipment [4, 64, 65].

5. Although it is practically not possible to avoid all transient surges occurring in field, but it is possible to reduce frequency of occurrence and magnitude of few transient surges like the switching surges.

### 1.4 Transient Modelling

Accurate modelling of the power system at higher frequencies and the characterization of measured transient phenomena is very important in order to detect the transient disturbance and their effects on power systems, to understand the system performance and operating reliability, and to optimally design equipment etc. [6, 9]. The transient overvoltages have a strong effect on quality control and reliability management in power systems. The determination of component ratings such as insulation levels and energy absorption capabilities, in the design and optimization process, for testing control and protection systems and for analyzing power systems requires a precise knowledge of the effect of transient overvoltages [11]. The most popular way to study the different types of transient overvoltages, and assessment of their effects is through mathematical modelling and
Simulations [66]. The specific model is designed depending on how and where it is to be used and on the purpose to be served in the power systems. The most important requirement is to correctly represent the actual components in a wide frequency range using the transient model. The model should be able to accurately reproduce the effects of transient overvoltages in terms of frequency, peak values, shape and attenuation of the voltage oscillations. Accurate modeling requires knowledge of the constituent components, accurate values of the inductances, capacitances, and resistances. The capacitance of components plays an important role in the transient response analysis at high frequencies. Transient models can be classified into two main groups [67]:

a) Time domain models: Distributed parameter and lumped parameter models are two commonly used approaches for transient modeling in time domain. Lumped parameter modeling is valid in low frequency range from 0.1 Hz to 3 kHz. The distributed parameter modeling is valid for frequency ranging from 50 Hz to 50 MHz.

b) Frequency domain models: The transient response is evaluated in the frequency domain. The time domain solution is found using inverse transformation algorithms such as the FFT (Fast Fourier Transform) of the transient response.

Simulation is an effective way for assessing effects of overvoltages on power equipment and analyzing power quality studies [68]. Several new techniques and software tools have been developed for studying and analyzing electromagnetic transients. Each simulation tool has its own advantages and disadvantages that make it more suitable for a specific kind of problem. The dissolved gas analysis, liquid chromatography, acoustic analysis, and transfer function techniques are few conventional methods used in impulse fault diagnosis. These methods fail to diagnose multiple faults and require experts to interpret the fault analysis results [69]. There has been considerable work done on fault diagnosis using artificial intelligence. Several useful and efficient fault location algorithms and simulation tools have been developed.
1.5 Objectives and Research Approach

This research work aims to investigate the effect of standard and non-standard impulse waveforms on three important power equipment: power transformer, insulated cable, and surge arrester. The main objective is to investigate the extent to which incident standard and non-standard lightning impulse waveform stresses the insulation of the power equipments. This is achieved by developing high frequency computational models of the high voltage power transformer, insulated cable and surge arrester. Efforts have been made to take into account the frequency-dependence of parameters and adequate representation of losses in the power equipment during transient simulations. The voltage appearing across the insulation (as a function of time) and the strength of insulation against the particular voltage wave is determined. Based on the test results, the waveforms which pose risk and are critical to insulation systems are identified. Most important applications of this study are:

1. Design and development of power equipment: Improvement can be made in the present designs for engineering optimization.
2. Identification and detection of impulse faults: Faults may be simulated deliberately within the computational models to study the fault characteristics.
3. Investigate the relevance of the reference standard waveforms used for lightning impulse tests.

1.6 Outline of the Chapters

The thesis is divided into six chapters followed by references.

The first chapter, *Overvoltage Surges and their Effects*, contains an overview of the electromagnetic transient phenomena that can occur on a power network. The present status of research on the transient overvoltages was reviewed along with the transient behaviour of power transformers, underground cables, and surge arresters. A brief introduction to electromagnetic surge modelling is also presented. This chapter also describes the objectives and approach of the present work, outline of chapters and main contributions of the thesis.

The second chapter, *Insulation coordination and Standards*, describes the background of insulation coordination and the relevant IEEE/IEC standards for impulse testing of power
equipment. The standard lightning and switching impulse wave shapes are also described briefly.

The third chapter, *Electric Stresses on Transformer Winding Insulation under Standard and Non-standard Impulse Voltages*, deals with experimental and computational study of impulse response of power transformer. It describes mathematical modelling of the power transformer in MATLAB©-Simulink and the transient response against the application of standard and non-standard impulse waveforms. Simulated results are compared with experimental results for validation of the model. Finally, the effects of impulse faults of different nature and different locations of occurrence in the high voltage winding of a transformer are presented.

The fourth chapter, *Electric Stresses on Cable Insulation under Standard and Non-standard Impulse Voltages*, discusses the transient analysis of insulated cables. The cable design, parameter determination and modelling method in MATLAB©-Simulink are presented. The transient response of the cable model against the application of standard and non-standard impulse waveforms is studied.

The fifth chapter, *Electric Stresses on Surge Arrester Insulation under Standard and Non-standard Impulse Voltages*, deals with the transient analysis of surge arresters. The surge arrester is modelled in MATLAB©-Simulink. Lightning impulse residual voltage test is performed for standard lightning impulse currents. The simulation results and manufacturer data are also compared for validation. The transient response of the Simulink model against the application of standard and non-standard impulse waveforms is studied.

The sixth chapter, *Conclusions and Future Scope of work*, concludes the thesis with an overall summary drawn from the work done and outlines the future scope of work.

1.7  **Original Contributions**

To the best of the knowledge of the author, the present work makes the following original contribution:

I. Study of effects of standard and non-standard lightning impulse waveforms on Power Transformer. A high frequency model is developed in MATLAB©-Simulink and
simulations have been carried out for the purpose of transient analysis as reported in Chapter 3.

II. Study of effects of standard and non-standard lightning impulse waveforms on insulated power cables. A high frequency model is developed in MATLAB\textsuperscript{©}-Simulink and simulations have been carried out for the purpose of transient analysis as reported in Chapter 4.

III. Study of effects of standard and non-standard lightning impulse waveforms on Surge arresters. A high frequency model is developed in MATLAB\textsuperscript{©}-Simulink and simulations have been carried out for the purpose of transient analysis as reported in Chapter 5.