INVESTIGATION OF WIND SPEED-DEPENDENT ELECTRIC POWER TRANSMISSION LINE MODELS

by

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ABSTRACT

SURYA NAGA KRISHNA MOHAN JAGARLAPUDI. Investigation of wind speed dependent electric power transmission line models. (Under the direction of DR.VALENTINA CECCHI)

Electric power transmission lines are a critical interconnection component of the power system. With the increasing demand for electric power and push for increased renewable generation, transmission lines are now operating close to their nominal ratings. This makes the grid increasingly vulnerable to service interruptions and blackouts. Given practical limitations posed on infrastructure upgrading, the optimized use of the existing delivery network is then of great importance. This thesis presents an approach to develop transmission line models that are able to account for: (i) available wind speed information, and (ii) changes in wind speed along the line length. Specifically, the line per unit length resistance is updated based on wind speed information, and the line model structure is determined based on the given wind speed variation along the line. A multi-segment lumped parameter line model structure is used to account for these longitudinal non-uniformities in line resistance due to the changes in wind speed along the length of the line. The proposed approach then uses the wind speed-dependent line models to determine power handling capabilities when the line is subjected to different wind speeds and wind profiles. Various case studies are presented to evaluate models' effectiveness and to show the influence of wind speed, and therefore of conductor temperature, on line maximum power transfer. Quantifiable differences between line models that do not take into account wind speed and the models that do are noted. Moreover, the resulting voltage stability boundaries are compared to the line thermal ratings to determine the most limiting factor.

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LIST OF SYMBOLS

Q_C	convective heat loss rate in per unit length
Q_S	rate of solar heat gain given in (weber/per unit length)
Q_R	radiation heat loss rate in per unit length.
K_F	thermal conductivity of air at temperature film
T_A	ambient temperature.
T_C	conductor temperature.
K_{ANGLE}	wind direction factor.
V_W	speed of air stream at conductor.
u_f	dynamic viscosity of air.
D	diameter of the conductor.
$\in$	emissivity.
φ	effective angle of incidence of the sun rays.
α	solar absorptive
A_S	total solar +sky radiated heat flux rate elevation corrected.
I_S	sending end current of the transmission line in (amperes)
U_S	sending end voltage of line in (kV)
U_R	receiving end voltage of line in (kV)
I_R	receiving end current of line in (amperes)
v_{C1}	wind speed of line segment 1 in m/s
v_{C2}	wind speed of line segment 2 in m/s
v_{CN}	nth line segment wind speed in m/s
T_{C1}	conductor temperature of line segment 1 in (°c)

T_{C2}	temperature of conductor for line segment 2 in (°c)
T_{CN}	nth line segment conductor temperature in (°c)
P_{MAX}	maximum power handling capability through transmission line
S_1	line segment 1
S_2	line segment 2
S_3	line segment 3
$Z\ (T_C(x))$	impedance, function of distance and conductor temperature.
R_{LINE}	resistance of transmission line

LIST OF ABBREVIATIONS

SLR	static line ratings
DLR	dynamic line ratings
HTLS	high temperature low sag
STL	short transmission line
MTL	medium transmission line
LTL	long transmission line
D.C	direct current
A.C	alternating current
ACSR	aluminum conductor steel reinforced

CHAPTER 1 : INTRODUCTION

1.1. Overview

Electric power systems consist of electrical components which supply, transfer and use electrical power. The objective of utilities is to meet load demand at consumer end and ensure quality and reliable power with high efficiency. In order to achieve above goal, utilities strive for maximum power transfer from generation to distribution with minimum real power losses and least cost. This thesis focuses on overhead electric power transmission lines as critical interconnection component of the power system. As constructing new transmission lines cannot be done with ease and it may not be economically feasible, this thesis presents a unique methodology to provide a better estimate of transmission line power handling capabilities based on available information of ambient conditions, with a focus on wind speed.

In this chapter the following topics are presented. First, background and motivation for this work is provided; then, relevant prior work is reviewed. Finally, an overview of the thesis and its organization is presented.

1.2. Background and Motivation

Electric power transmission lines are a critical network component of the power system. With the ever-increasing demand for electric power, transmission lines are now operating beyond their nominal ratings [1]. Given practical limitations posed on infrastructure upgrading the optimized use of the existing assets is of great importance.

Mainly economic and space constraints limit the power companies' ability to perform re-conducting or re-structuring of existing transmission lines, as well as to construct new transmission links. For these reasons, it has become extremely relevant to be able to accurately determine the line power handling capabilities, limited by line thermal ratings and by voltage stability limits.

An important set of parameters to be taken into account is environmental conditions, which are critical to accurately determine line power handling capabilities [2]-[6]. This is especially relevant when there is high correlation between the flow of power and an environmental cooling effect on a conductor, e.g. high power flows from high-wind-speed wind generation may be accommodated since the high wind speeds cool the line. Significant work has been performed in *dynamic line ratings (DLR)* (e.g. [7]-[12]), in which ambient conditions and current flow are used to determine true line thermal rating in real-time; this can improve system reliability while optimizing utilization of transmission lines. However, most utilities utilize *static line ratings (SLR*) based on seasonal weather conditions.

Static Line Ratings (SLR) indicate maximum amount of current that the line conductors can carry, under a set of assumed weather conditions, without violating clearance safety codes or damaging the conductor [2]. Transmission line SLR are usually calculated for constant weather conditions considered over a period of time. As a result, continuous monitoring of weather conditions and installation of new equipment on overhead conductor is not required. For example, the UK Energy Association's Engineering Recommendation P27 [13] sets ratings based on the following assumed average values: (i) ambient temperature of 2 °C, 9 °C and 20 °C in winter, fall/spring and summer, respectively, (ii) wind speed of 0.5 m/s, and (iii) effect of solar radiation is not taken into account. Usually SLR are considered too conservative in most circumstances, especially under high wind conditions where the wind cooling effects can lower the conductor temperature and therefore allow for a higher current. Therefore, the utilization of the existing network can be maximized if the line ampacity can be identified in real time, based on atmospheric parameters such as ambient temperature, wind speed and direction, and solar radiation. In a study presented in [2], it was concluded that an additional 54% energy yield from distributed generation could be accommodated through deployment of a DLR system. It is important to note that a dynamic rating system could be used to increase visibility of conditions both off-line (to inform system planning) and on-line (to increase component utilization) [2]. It is also important to note that real-time rating determination may lead, at times, to lower-than-static ratings (for example during long periods of low wind speed), which is even more critical with respect to ensuring safety.

Dynamic Line Ratings (DLR) for transmission lines are calculated for current (real-time or close to real-time) varying weather and physical conditions. Due to this, DLR often results in an increase in allowable loading of existing resources and therefore affects a utility's load management system. Ambient temperature and heat transfer by wind have a strong influence on power line transmission loadability. For these reasons, with the use of DLR systems, an increase in power transfer may be possible using the same resources (lines) while yielding increased efficiency and greater flexibility for network power-flows [3].

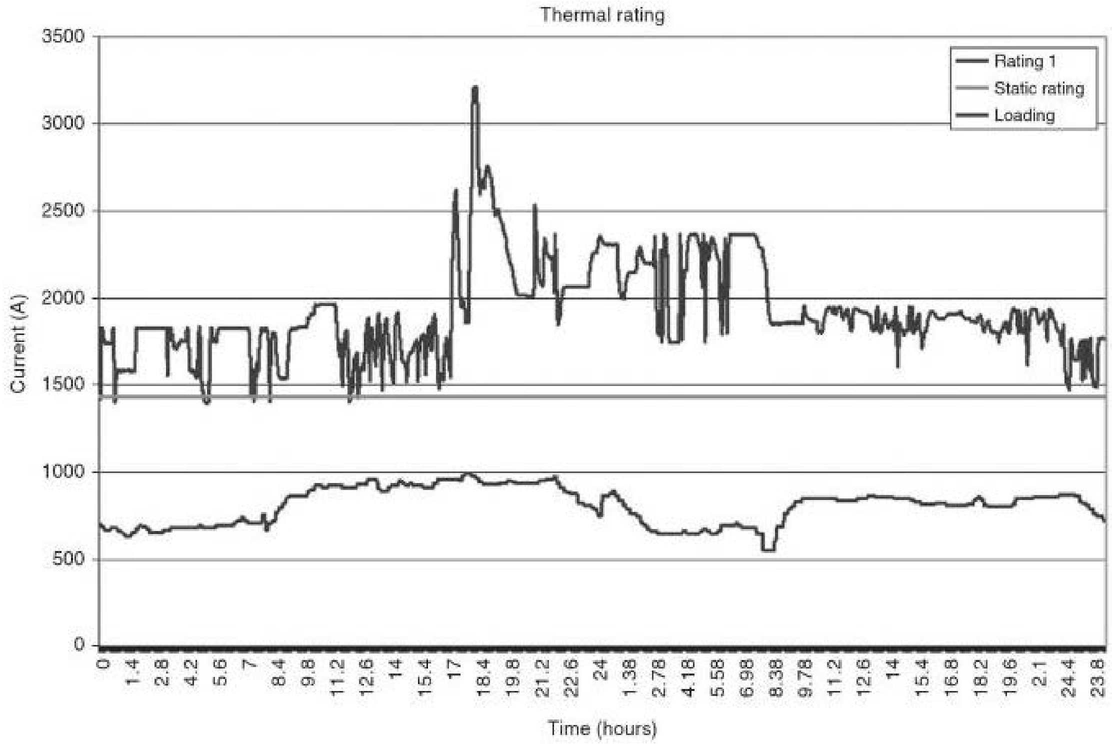

FIGURE 1.1: Dynamic thermal rating profile of a transmission line in Malaysia [14]

The figure 1.1 indicate the static line rating and dynamic line ratings for specific load variations.

There are several DLR monitoring methods which have been devised and can be classified into either online methods or offline methods. The following are some of the methods which are used to monitor the DLR of power transmission lines. Three approaches: 1. weather based, 2. sag based, and 3. tension based, are briefly described below [11].

Weather based DLR - Instantaneous conductor temperature is obtained using environmental conditions to which a conductor is exposed and its heat balance is calculated. This value is used to determine a suitable line rating which allows the conductor to operate within the specified limits of operability. The field data needed are:

- Wind speed (measured by an anemometer) and wind direction
- Air temperature
- Solar heat intensity
- Conductor parameters such as diameter, ac resistance, rates of heat losses and heat gains.

Sag based DLR - This method is based on the determination of the amount of current that can be carried without exceeding the required statutory ground clearance. The field data are the same as that of weather based approach. Additional data include conductor position and sag. After the required data is collected, the conductor’s actual temperature is calculated using the predetermined relationship between conductor position/ sag and temperature. The heat balance equation is then used to determine how much more current can be transferred before the maximum operating temperature of the conductor is met and exceeded.

Tension based DLR - When a conductor is exposed to extreme conditions over an extended period of time, annealing occurs. Annealing due to excessive line temperature is one of the most significant causes of conductor aging, one of the main reasons for permanent damage of Aluminum strands in ACSR conductors [12]. When stranded conductors are subjected to high operating temperatures, the strands are exposed to a lot of heat. This heat relaxes the strands, causing the conductor to elongate and lose strength. In tension monitoring DLR methods, a tension gauge is placed on the conductor; and the line tension and strain are measured.

Thermal limit is the maximum allowable current flowing through transmission line before it breaks down due to overheating. Power line ampacity is dependent on several features and impacts transmission line spans. DLR takes more efficient advantage of the line ampacity because of inclusion of real time monitoring of weather parameters like wind speed in calculating line ampacity [4]. The power line ampacity is determined by the most limited section on the whole line length which can be defined usually for the one with having higher conductor temperature. The line current is the variable that defines the thermal limiting value .One possible method to increase line ampacity is to change the conductor type, e.g. a larger standard conductor or a high temperature low sag (HTLS) conductor or, for smaller capacity increase need, to perform conductor re-tensioning or to increase tower height. Another way is to use DLR which may give better way of calculating ampacity and may be more economical. Periodic or continuous measurement of these values allows the thermal limit of the line to be regularly updated and maximized [9].

Another important consideration is that electric power lines are exposed to different geographic and weather conditions, such as wind speed, which affect the temperature of the conductor; because of this, transmission lines effectively have varying line parameter values along their length. Transmission lines are traditionally modeled through a uniformly distributed parameter (e.g. [15]-[17]) or a lumped parameter configuration which assume uniform distribution of line parameters. However, wind speed varies as position along the transmission line changes and results in changes in conductor temperature and therefore in line electrical parameter along the line. To account for this non-uniformity of line parameters along the line, in this thesis, a multi segment lumped parameter model structure is used.

This thesis discusses the importance of considering weather conditions such as daily average wind speeds and real time wind speed information not only to determine line thermal ratings, but also to be used in the line model to better estimate line power handling capabilities. Wind speed influences the conductor cooling-rate and provides cooling, principally by means of convective heat loss, to the surrounding air. It plays crucial role in accurately determining maximum allowable current and maximum power handling capabilities of transmission line.

1.3. Prior Work

This chapter includes a survey of scholarly publications in regards to weather-dependent transmission line models. In [18], the focus is on the effect of ambient temperature on conductor temperature and line parameters. Line power handling capabilities were determined for transmission line models which incorporate only ambient temperature (weather parameter) to obtain line parameter values. Given the transmission network spans in different geographical areas there can be considerable variations in line parameters due to other weather conditions like altitude, wind, pressure, etc. Prior to the proposed approach, transmission line models did not take into account conductor temperature variations along the transmission lines and conductor temperature was always assumed constant with distance along the line.

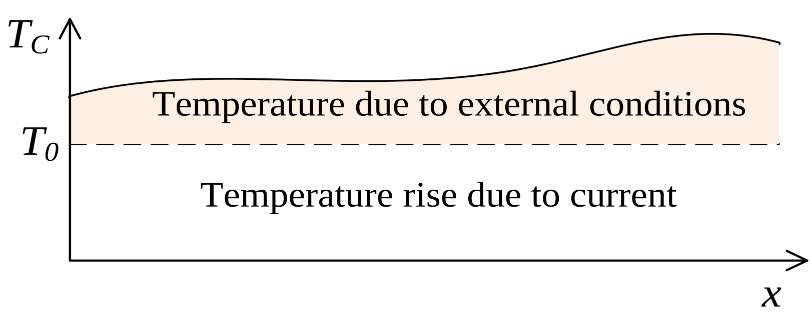

FIGURE 1.2: Example graphical representation of conductor temperature, T_C, vs. distance along the line, x [19]

However further research in the area made path to develop and propose a methodology which accounts for ambient temperatures along the length of transmission line for calculating transmission line parameter values. The line modeling algorithm consists of four main steps [18]:

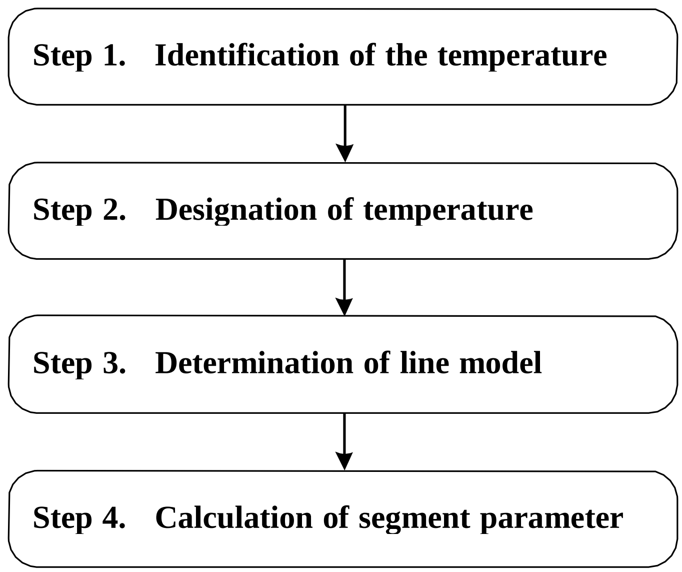

FIGURE 1.3: Steps required to incorporate ambient conditions in line models [18]

In order to calculate line segment parameter values the first step is identification of temperature profile. The idea of incorporating available ambient temperature measurement information within the line models along the length of transmission line was to get accurate performance of transmission line.

To determine dynamic line ratings it's necessary to account varying ambient temperatures while modeling transmission lines. To account for non-uniform ambient temperatures along the length of transmission line several line modeling techniques where developed to calculate transmission line parameter values [20]. Line models that incorporate ambient temperature variations along the line were modeled assuming that loading conditions are fixed, i.e. load current I or load resistance is constant and do not change with change in the ambient temperature. Various ways of incorporating available temperature information were studied, like including ambient temperature in:

- Distributed parameter models, and
- Lumped parameter models (single and multi-segment).

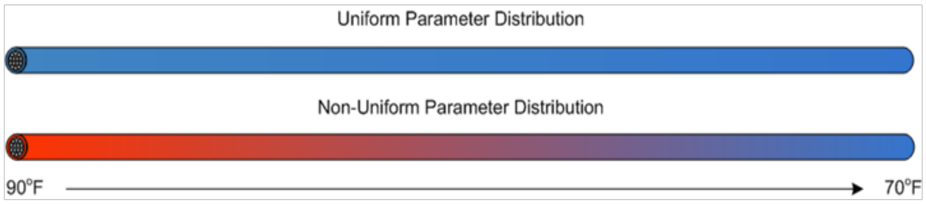

FIGURE 1.4: Differences between uniform and non-uniform parameter distribution [21]

Figure 1.4 represents uniform and non-uniform parameter distribution dependent on conductor temperature variations along the length of transmission line

In order to address the non-uniformity of line parameters along the line, caused by an ambient temperature gradient, a non-uniformly distributed parameter model was developed. The non-uniformly distributed parameter model is characterized by a dependency of the line distributed impedance on distance along the line [20]. A lumped parameter model composed of multiple non-uniform segments can also be used to approximate the non-uniformly distributed parameter model. With developed line models, ambient temperature variations along the line were shown to affect steady-state terminal voltages and line currents. These effects increased for severe temperature gradients, especially in terms of line power handling capabilities. The developed line models are temperature-dependent, in terms of both their structure and line parameters; therefore, they enable capturing of temperature effects .

In [18]-[20], several aspects were not addressed:

- The transmission lines models do not consider the impact of wind speed cooling while calculating transmission line parameter values and in obtaining maximum power handling capabilities and ampacity of the transmission line.
- Loading conditions were assumed to be constant and assumed to be independent of line models.

This thesis accounts for the aforementioned aspects, and proposes a methodology to incorporate wind speeds into transmission line modeling. Specifically, the proposed modeling approach accounts for: (i) available wind speed information, and (ii) changes in wind speed along the line length. Specifically, the line per unit length resistance is updated based on wind speed information, and the line model structure is determined based on the given wind speed variation along the line. A multi-segment lumped parameter line model structure is used to account for these longitudinal non-uniformities in line resistance due to the changes in wind speed along the length of the line. The proposed approach then uses the wind speed-dependent line models to determine power handling capabilities when the line is subjected to different wind speeds and wind profiles along the line.

1.4. Thesis Overview and Organization

The thesis is organized as follows:

CHAPTER 2 presents relevant background knowledge in regards to transmission line modeling and dependence of line parameters on wind speed. Relationship between current and conductor temperature is explained by reviewing IEEE-738 heat balance equation. In addition dependency of line parameter values on wind speed is described. The chapter then highlights non-uniform distribution of line parameters based on wind speed variations along the transmission line .Finally chapter 2 gives a review of line transfer capability limits and their link to the work in this thesis.

CHAPTER 3 formulates the problem statement that is addressed in this thesis. It presents the research questions and hypotheses. Line modeling assumptions are also explained. Finally, novel line model structures, including the non-uniformly distributed parameter and the multi-segment lumped parameter line models are explained.

CHAPTER 4 describes the method proposed to incorporate wind speed in transmission line models. A step by step procedure is presented to determine model structure, conductor temperatures, and corresponding line parameter values, given wind speed information.

In CHAPTER 5, case studies and simulation results are presented to highlight variations in line power handling capabilities based on: 1) Changes in conductor temperature, 2) Changes in wind speed, and 3) Non-uniformities of wind speed along the length of the transmission line. Comparison of thermal and voltage stability limits are also emphasized. The summary of results and observations then focuses on the noted importance of wind speed in better estimate of conductor temperature and therefore of maximum power transfer.

Finally, CHAPTER 6 provides a summary of research contributions and presents a vision for future research direction.

CHAPTER 2 : TRANSMISSION LINE MODELING AND RELATIONSHIP TO WIND SPEED

2.1. Overview

This chapter provides a review of fundamental knowledge needed to address and tackle the objectives of this thesis. It first reviews traditional ways to model transmission lines (2.2), including the distributed parameter line model and the lumped parameter line model and highlights the dependency of line parameters on wind speed (2.3).It then explains how this dependency could bring about non-uniform distribution of the line electrical parameters (2.4). Finally, in section (2.5) it gives an overview of line power transfer capacity limits, highlighting how line models may affect them.

2.2. Review of Transmission Line Modeling

Electric power transmission lines play a key role in transferring power from power plants to consumers at load side. Transmission lines have four distributed electrical parameters that describe voltage and current relationships: series resistance, series inductance, shunt capacitance, and shunt conductance. The distributed resistance and inductance form the series impedance of the line, while the capacitance and the conductance present between conductors or conductor to neutral form the shunt admittance of the line.

Line parameter values change with material characteristics of conductor and based on electric and magnetic fields surrounding the conductor. Hence geometric distances play a vital role in finding these distributed line parameter values [22]. The conductor resistance changes with change in conductor temperature. Direct Current (DC) resistance of a conductor is given by the following equation:

$$R = \frac{\rho l}{A} (\Omega)$$

Where

R: Direct Current (DC) resistance of conductor

l :length of transmission line

ρ : Coefficient of resistivity

A: Area of cross section of conductor.

The equation for resistance is accurate for steady state analysis as it does not depend on frequency and considered to be DC resistance. Expression for resistive loss is defined as:

$$R = \frac{\rho_{loss}}{I^2} (\Omega)$$

Where

ρ_{loss} : Ohmic Loss

I: Current flowing in conductor

R: Effective resistance of conductor

In case of DC current, the distribution is uniform throughout the conductor. Non-uniform distribution of current over surface of conductor results in skin effect. Unlike for DC resistance which is independent of frequency, skin effect can be observed in Alternating Current (AC) resistance [23].

In order to study the line as part of the power system, it is important to be able to determine how line parameters influence the flow of power through the system.

Specifically, voltage and current relationships along the lines are needed. A method to model transmission lines is through a uniformly distributed parameter configuration, the distributed parameter model. A simplification of this model is more commonly utilized for studies on power system behavior. These models are mostly interested in the nodal behavior of the system, and therefore on the line terminal behavior. Using the distributed parameter model would be time-consuming and relatively difficult with mathematical calculations. Therefore, simplified line model is often used. The simplification of the distributed parameter model consists on adopting a lumped parameter configuration of the line that maintains the same terminal behavior as the distributed line model [15][16]. Examples of these simplified models are the lumped pi and gamma forms.

The next two subsections will present a review of the distributed parameter model and of the lumped parameter model, respectively. The focus will be put on showing why the lumped parameter models are so widely used and why they are considered acceptable.

2.2.1. Distributed Parameter Line Model

In case of distributed model, transmission line parameters like series impedance and shunt admittance are uniformly distributed in nature. The aforementioned line parameters are measured in per unit length. The line model comprises differential components with series impedances and shunt admittances calculated in per unit lengths. The following equations give expressions for impedance and admittance in per unit length.

$$z = r + jX_L$$

$$y = g + jXc$$

Where,

z: series impedance in per unit length

y: shunt admittance in per unit length

r : series resistance (ohm/unit length)

X_L: series inductance (ohms/unit length)

X_C: shunt capacitance (ohms/unit length)

A differential section of the distributed line model is shown in figure 2.1 for a section of length *dx*. Its series impedance and shunt admittance are then *z dx* and *y dx*, respectively.

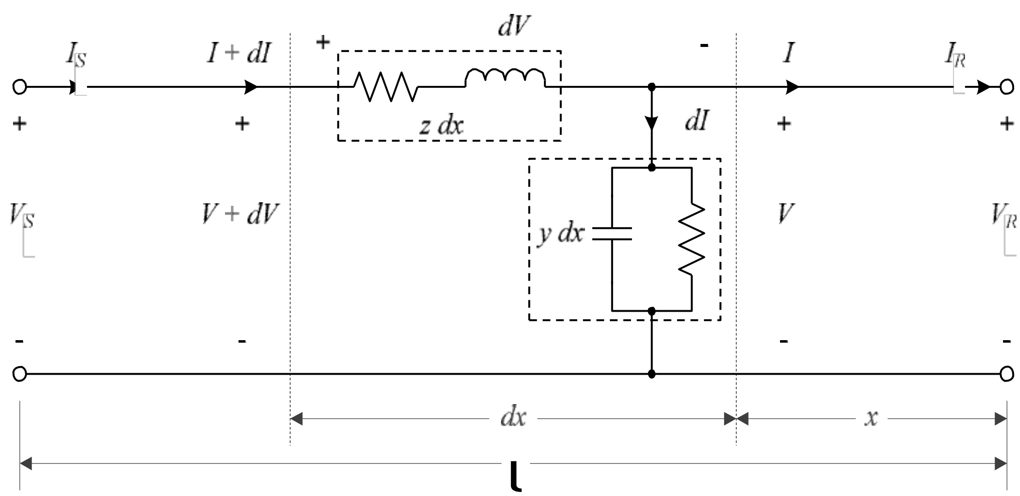

FIGURE 2.1: Uniform distributed parameter line model [22]

With line parameters, voltage and current quantities as defined in figure 2.1, the relationships between the terminal voltages and currents can be defined with the following 1st-order differential equations [22]:

$$\gamma = \sqrt{yz}$$

$$\frac{dV}{dx} = zI$$

$$\frac{dI}{dx} = yV$$

Or with either of following 2nd order equations:

$$\frac{d^2V}{dx^2} = yzV = \gamma 2V$$

$$\frac{d^2I}{dx^2} = yzV = \gamma 2V$$

Solving the differential equations gives the following voltage and current equations in terms of *x*, point along the line:

$$V = V_R \cosh(\gamma x) + Z_c I_R \sinh(\gamma x)$$
$$I = I_R \cosh(\gamma x) + \frac{V_R}{Z_c} I_R \sinh(\gamma x)$$

As mathematically expressed by the above equations, with the distributed line model the steady-state voltages and currents can be determined at any point along the line. However, the relationship between the terminal voltages and the terminal currents, i.e. at the sending and receiving ends, are often sufficient in power system studies since nodal analysis is conducted.

$$V_S = V_R \cosh(\gamma l) + Z_c I_R \sinh(\gamma l)$$
$$I_S = I_R \cosh(\gamma l) + \frac{V_R}{Z_c} I_R \sinh(\gamma l)$$

In next section simplified lumped parameter line models are developed. It should be noted that voltage and current line behavior of lumped type will mostly remain same as that of distributed transmission line model.

2.2.2. Lumped Parameter Line Models

The lumped-equivalent circuits are obtained by selecting the model components Z and Y so that the terminal behavior of the distributed line model is not changed with the use of passive elements (resistance, inductance, and capacitance). Different types of lumped transmission line models are Nominal (π) and Nominal (τ) [15][16].

Lumped Type -Nominal (π) Transmission Line Model

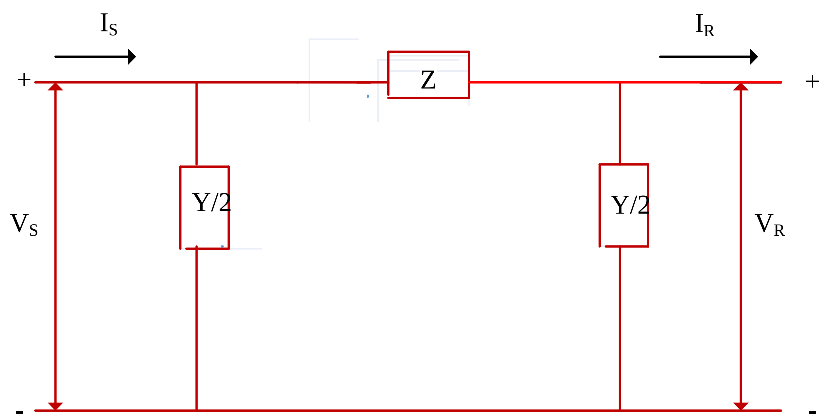

FIGURE 2.2 : Lumped type- nominal transmission(π) line model with V_S,V_R,I_S,I_R,Z,Y/2 being sending, receiving end voltage, sending end current ,receiving end current, impedance, admittance respectively [15]

Lumped Type -Nominal (τ) Transmission Line Model

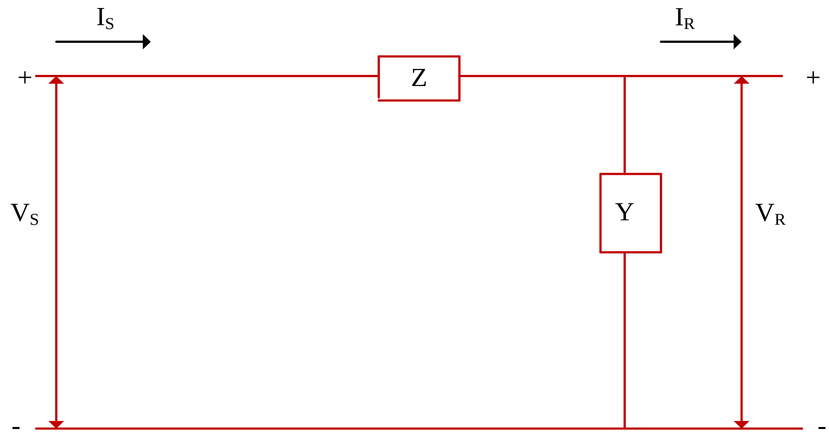

FIGURE 2.3: Lumped type- nominal transmission(τ) line model with V_S,V_R ,I_S,I_R,Z,Y being sending ,receiving end voltage, sending end current, receiving end current, impedance, admittance respectively [15]

Applying the KVL (mesh analysis) and KCL (nodal analysis) to the above figures 2.2 and 2.3,the receiving end voltage and receiving end current for the transmission line can be obtained. Compared to distributed models, lumped parameter models are more precise and easy for obtaining outputs like power, voltage and current from transmission line as it does not involve huge computations in form of large differential equations. Significant advantage of lumped parameter transmission line model is accuracy of terminal behavior will be higher than for distributed line modeling.

The following sub-section discusses the significance of heat balance equation which gives a relation between the conductor temperature, the line resistance and the wind speed. It further presents an equation correlating resistance of transmission line and conductor temperature via wind speed.

2.3. Dependency of Line Parameters on Wind Speed

An overview of heat balance equation is presented in this section. Two different types of heat balance equations can be considered to obtain conductor temperature and current relationship depending on necessity. They are steady state heat balance and non-steady state heat balance equations. Heat balance equation can be used in either of the following ways:

- To calculate maximum allowable conductor temperature if the current is known which can be determined by using steady state heat balance equation.
- To obtain current flowing in conductor if maximum allowable temperature is given which can be determined with help of non-steady state heat balance equation

The IEEE 738-2006 defines a steady state heat balance equation which gives relation between conductor temperature, current, wind speeds [24]-[26].

Temperature of conductor depends on following factors,

- Conductor material properties
- Conductor diameter
- Ambient conditions
- Surface conditions
- Electric current of conductor

The line resistance is function of conductor temperature and it is important to observe impact of wind speed on conductor temperature and resistance.

Steady State Heat Balance Equation

For typical drake conductor if convective cooling (Q_C) and weather conditions like ambient temperature, wind speed (v), radiation (Q_R), solar heat gain (Q_S) and maximum allowable current (I) passing through conductor are known in heat balance equation then, conductor of temperature can be determined by following mathematical expression [25].

$$Q_C + Q_R = Q_S + I^2 R(\mathrm{T_C})$$

Where,

$$Q_S = \alpha * \mathrm{A_S} * \sin(\vartheta)$$

$$Q_C = (0.0019(D*(\frac{v}{\mu_F})^{0.6})*\mathrm{K_F}*\mathrm{K_{ANGLE}}*(\mathrm{T_C} - \mathrm{T_A}))$$

$$Q_R = 0.0178*\mathrm{D}*\in*(\frac{T_C+273}{100})^4 - (\frac{T_A+273}{100})^4$$

Q_C: Convective heat loss rate in per unit length

Q_S: Rate of solar heat gain given in per unit length

Q_R: Radiation heat loss rate in per unit length.

Definition of terms shown in above equations are as follows

K_F: Thermal conductivity of air at temperature film

T_A: Ambient temperature.

T_C: Conductor temperature.

K_{ANGLE}: Wind direction factor.

v: Speed of air stream at conductor.

u_F: Dynamic viscosity of air.

D: Diameter of the conductor.

$\in$: Emissivity.

ϑ: Effective angle of incidence of the sun rays.

α :Solar absorptive

A_S: Total solar +sky radiated heat flux rate elevation corrected.

R (T_C): Resistance for typical drake conductor calculated at conductor temperature (T_C)

I: Current flowing through conductor for a particular load value

Following section describes equation to calculate line parameters dependent on conductor temperature via wind speed.

Equation relating conductor temperature and resistance

Given a conductor operating at a reference temperature T_O with temperature coefficient of resistance (β) and resistance $R(T_O)$, the new value of resistance $R(T_C)$ calculated at a conductor temperature T_C is given by the equation [18]:

$$R(T_C) = R(T_O)(1+\beta(T_C - T_O)$$

2.4. Non-Uniform Distribution of Line Parameters

Generally the line parameters are calculated assuming that the conductor temperature or weather parameters are constant for the entire section of transmission line. However given the changes in weather and geography changes, there is a possibility to not achieve accurate results when the transmission line is modeled assuming a constant temperature along its length. The idea is to develop a line model such that all the transmission line parameter values are calculated by incorporating the non-uniformities along the length of the transmission line. The line model divided will consist of number of line sections in which each line section line parameter values are calculated based on own section weather conditions. This will certainly result in varying line parameters .To incorporate these variations while modeling transmission line parameter values, a non-uniform distributed line model is developed.

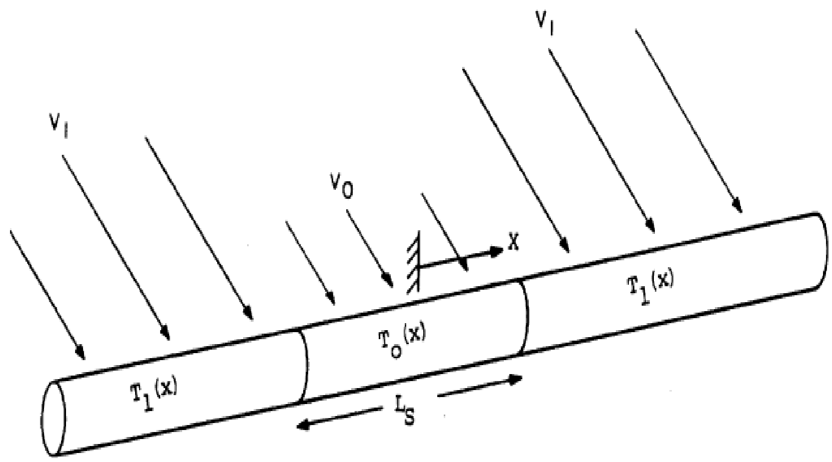

FIGURE 2.4: Wind shielding as source of non-uniformity [27]

The figure 2.4 indicates wind shielding as source of non-uniformity where different sections of the line are operating at its own wind speed and dependent on position.

Taking into account variations in wind speed along the line, implies:

- A change in line parameters at a particular point along the line, *x*, due to the change in wind speed and T_C and its effects on line parameters,
- A non-uniformity in line parameters along the line based on wind speed gradients.

By allowing the per-unit length parameters to vary with *x*, a non-uniformly distributed parameter model of the line can be developed

In section 3.4.1 a detailed analysis of non-uniform distributed line model is presented.

2.5. Transfer Capabilities of Transmission Line

Maximum power that can be transferred over a transmission line is called the transfer capability. The transfer of electric power for transmission network is usually limited by the physical and electrical characteristics of the system. Mainly depending upon their lengths, transmission lines have limitations over their power handling capability [28]. For short transmission lines of less than 80 km, thermal limits are the constraints in terms of the line transfer capabilities. For transmission lines of lengths between 80 and 250 km, classified as, medium transmission lines, the limiting factor is usually voltage limits. In regards to voltage stability limits, the line maximum power transfer point can be obtained by constructing the real power vs voltage curve, i.e. the PV or nose curve [29]. The limiting factor for long transmission lines, i.e. longer than 250 km, are usually steady state limits. The ability of power system getting back to steady state after losing synchronism is called steady state stability.

However, the classification of transfer capability limits based on line lengths alone may not give a complete idea. Transfer capability of transmission lines can also be dependent on strength and source of load. Hence, NERC (National American Electric Reliability Council) as defined transfer capability to be the minimum among thermal, voltage and steady state stability limits [30]:

Transfer capabilities = minimum (thermal limits, voltage limit, stability limit)

Next, Chapter 3 gives an overview of the problem statement by discussing the hypothesis and research questions associated with ampacity and maximum power handling capabilities of a transmission line and their relationship to wind speed. Chapter 4 then presents the proposed methodology to calculate the resistance of transmission line incorporating ambient condition like wind speed and subsequent section followed with explanation of step by step procedure to obtain relation between wind speeds, resistance of line via conductor temperature.

CHAPTER 3 : PROBLEM STATEMENT

3.1. Overview

This chapter discusses the problem statement and explains challenges and research questions that the work presented in this thesis is addressing. First, research hypothesis is presented in section 3.2; then, section 3.3 presents assumptions considered for wind-speed dependent modeling of transmission lines. Section 3.4 finally reviews line model structures that can be used to incorporate wind speed information and describes the need for line model segmentation to incorporate non-uniformities of wind speed along the length of the transmission line.

3.2. Research Questions and Hypothesis

This section addresses the problem statement for the thesis articulated in the form of hypothesis and research questions. Premise for the thesis was to study impact of wind speed, and consequently of conductor temperatures, on maximum power handling capabilities of transmission line. Based on this premise, the following questions were investigated in this thesis.

- Does wind speed affect conductor temperature?
- Does wind speed affect transmission line parameters?
- Does wind speed variation *along* a line affect its power handling capabilities?

If YES, how can we model the line such that it captures the variations

- Available wind speed information → changes in line parameters
- Changes in wind speed along the line → non-uniformity of line parameters along the line

3.3. Modeling Assumptions

When modeling the transmission line, the following assumptions were made:

- Inductances and capacitances of a lumped parameter line model (e.g. the PI model) are constant and do not change with wind speed and conductor temperature. Inductance and capacitance per unit length values will not change with wind speed and conductor temperature; overall line model inductance and capacitance will only change based on the line (or segment) length.
- With the exception of wind speed, all other weather conditions, such as humidity, solar radiation, and ambient temperature, are presumed to be at a constant value and not to change along the line.
- Current density is uniform along the entire transmission line, which would result in any non-uniformity in conductor temperature and therefore in line parameters along the line to be solely due to changes in wind speed along the line.
- Transmission line charging currents through capacitances are assumed negligible.

3.4. Line Model Structures

Considering the hypothesis and questions, which challenge transmission line parameter values, several line modeling structures are explained in this section, based on the modeling assumptions. For the analysis, in this thesis the lumped parameter transmission line model is considered. Firstly, for a lumped parameter line model with single line segment, line parameter values are calculated based on single value of conductor temperature which is obtained from single wind speed measurement for entire section of transmission line. Secondly, to incorporate non-uniformities of wind speed in line parameters and to get a better estimate for power handling capabilities and ampacity of transmission line either non-uniformly distributed parameter line model or multi-segment lumped parameter line model structure can be considered.

3.4.1. Non-Uniformly Distributed Line Model

Traditionally, uniform distributed line models are considered and line parameter values calculated are uniformly distributed and are not dependent on changes along the length of transmission line. It is noted that the traditional uniformly distributed parameter model is not able to represent this non-uniformity of line parameters along the line, i.e. per unit length parameters z and y. The non-uniformly distributed parameter model is characterized by a dependency of the line distributed impedance on distance along the line [20].

$$z(x) = z + \Delta z(x)$$

The line distributed shunt admittance, y, is not considered to be a function of x.

The distributed series impedance of the line, z, is a function of wind speed $v(x)$, which changes with distance along the line, x

$$z(v(x)) = r(v(x) + jX_L(x)$$

To overcome the above problem non-uniform distributed line model can be used as shown in figure 3.1 which accounts for non-uniformities of wind speeds while calculating transmission line parameter values.

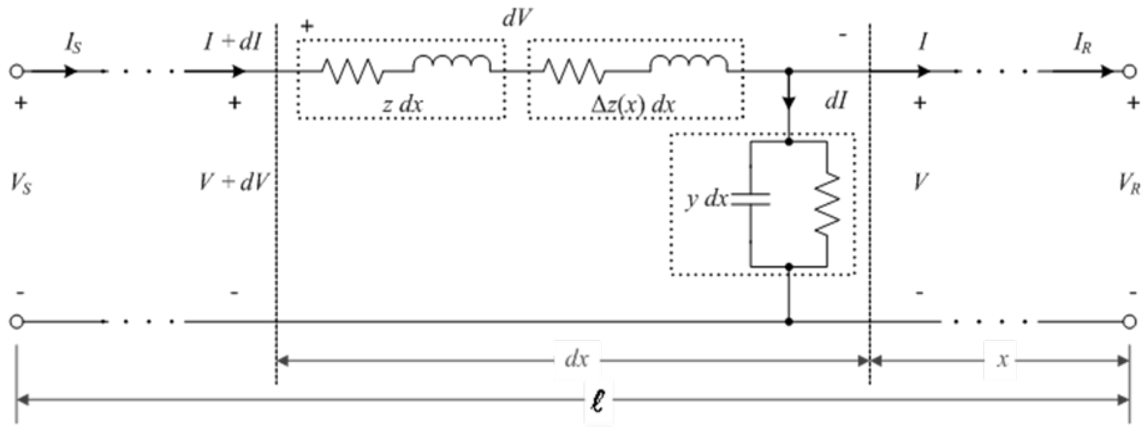

FIGURE 3.1:Non-uniform distributed line model [20]

Due to non-uniformities the impedance values of line change with change in wind speed and distance. As seen in section 2.2.1 and 2.4 distributed line models involves mathematical equations with large differential equations needing to be solved. Due to computational difficulties and more time consumption these line models are generally not considered for analysis of transmission lines. Thus lumped (π) transmission line model is considered in this thesis because of relatively higher computational efficiency. The Main focus would be on lumped uniform and non-uniform transmission line models. A lumped line model is divided into multiple lumped line segments in which each line segment parameter values calculated can either incorporate non-uniformities of wind speed or distance or both while modeling line parameter values.

Following sections explain need and difference between the multiple uniform lumped line segments and multiple non-uniform lumped line segments.

3.4.2. Multi-Segment Lumped Parameter Line Model

Multiple Equal-Length Segment Lumped Parameter Line Model

To understand non-uniformities of wind speed gradient alone in calculation of line parameter values, multi-uniform lumped line segmentation is considered. In this, the transmission line is divided into multiple uniform segments in which each line segment is of same length but different parameter values based on the changes in wind speed along the length of the transmission line [19][31]. A graphical representation is shown in figure 3.2.

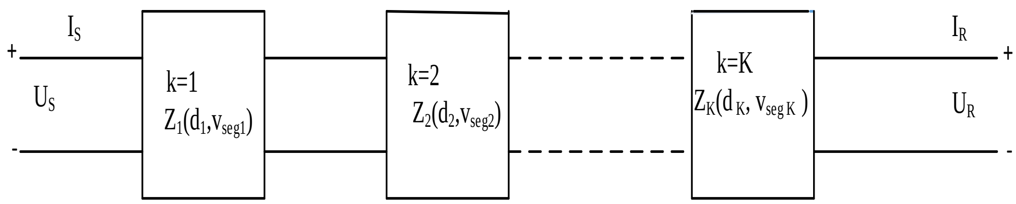

FIGURE 3.2: Representation of model structure for cascaded network of *K*-Segments, each at different wind Speed (and subsequently different T_C) [19]

Where,

U_S: Sending end voltage

U_R: Receiving end voltage

I_S: Sending end current

I_R: Receiving end current

d_1: Length of first segment

d_2: Length of second segment

d_K: Length of Kth segment

Z_1 (d_1, vseg1): Impedance of segment 1

Z_2 (d_2, vseg2): Impedance of segment 2

Z_K (d_K, v_{segK}): Impedance of segment K

The figure indicates that each line segment parameters are modeled at its corresponding wind speed and line parameters of each segment as different length and impedance (resistance) per unit length.

Multiple Non-Uniform Segment Lumped Parameter Line Model

In non-uniform lumped-parameter line model segmentation, the appropriate model segmentation is determined based on the given wind speed gradient along the line, then transmission line parameter values for each segment are calculated to account for the specific wind speed that characterizes each line model section. A Matlab representation of an example multi-segment lumped parameter line model is shown in APPENDIX A. The case studies and test results corresponding to section 3.4.2 are described in chapters 4 and 5.

The following chapter introduces the methodology and the proposed step by step procedure used to incorporate wind speeds into transmission line modeling and further it discuss the importance of using the proposed approach to incorporate non-uniformities of wind speeds in case of multi-uniform and non-uniform lumped line segmented models.

CHAPTER 4 : PROPOSED APPROACH

4.1. Overview

This chapter introduces novel technique to get better estimate of line power transfer capabilities and ampacity of transmission line and explains co-relation between wind speed and resistance of transmission line to obtain the above results. It presents the proposed line modeling approach used to incorporate wind speed information into the line model. Specifically, line electrical parameters are updated based on available wind speed information (4.2.1) and variations of wind speed and subsequent non-uniform distribution of line parameters, along the line are accounted for by using a multi-segment line model structure (4.2.2).

4.2. Incorporating Wind Speed Information: Line Modeling Approach

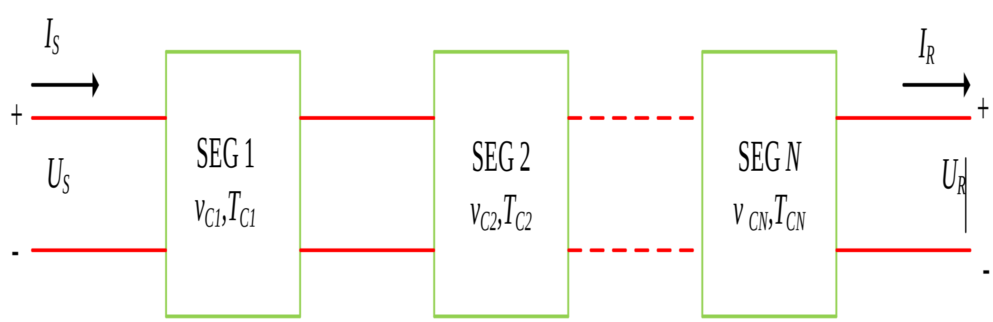

FIGURE 4.1: Block diagram of N-segment line model with each line segment at a corresponding wind speed (v_{C1} ,v_{C2} ----v_{CN}) in m/s and corresponding conductor temperatures(T_{C1}, T_{C2}---- T_{CN}) in degrees Celsius (°C) and I_S,I_R,U_S,U_R being sending end current, receiving end current, sending end voltage and receiving end voltage respectively

The line model segmentation depends on the wind speed gradient along the line.

The approach used to incorporate available wind speed information into the line models is two folded:

1) Develop relationship to update line electrical parameters (R, L, C) based on the wind speed value;
2) Determine an appropriate line model structure (i.e. segmentation) to account for non-uniformities of line electrical parameters along the line due to a wind speed gradient along the length of the transmission line.

Line Model Parameters

I_S: Sending end current of the transmission line

U_S: Sending end voltage of line

$U_{R:}$ Receiving end voltage of line

$I_{R:}$ Receiving end current of line

v_{C1}: Wind speed of line segment 1

v_{C2}: Wind speed of line segment 2

$v_{CN:}$ Nth line segment wind speed

T_{C1}: Conductor temperature of line segment 1

T_{C2}: Temperature of conductor for line segment 2

$T_{CN:}$ Nth line segment conductor temperature

4.2.1. From Wind Speed to Updated Line Parameters

The following block diagram represents the way to incorporate wind speed (v) into the transmission line modeling.

Line model developed can account wind speed in following ways:

- Available wind speed information

  → From wind speed to updated line parameters

- Changes in wind speed along the line

  → From wind speed profile to multi-segment line model structure

In the line model only resistance parameter changes with the wind speed and inductance and capacitance does not change with wind speeds.

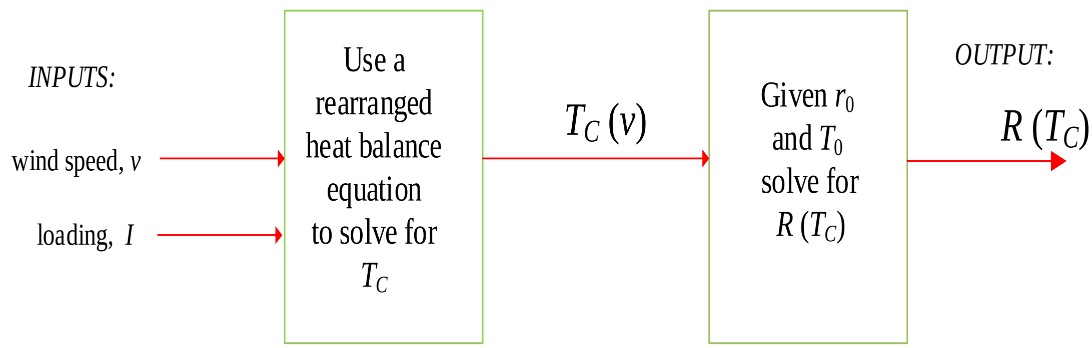

FIGURE 4.2: Proposed modeling approach with inputs (wind speed (*v*) in m/s, current (*I*) from steady state equation and (R_O) being reference resistance,(T_O) being reference conductor temperature, with conductor temperature (T_C), line resistance of conductor R (T_C)) and outputs (power in (MW) and receiving end voltage (U_R)),*d* is the length of the line

From figure (4.2)

Inputs

v: Wind speed of transmission line

I: Current obtained from steady state equation

Note: The current value is obtained for a load value (modeled as constant impedance load) which was considered from voltage stability (PV) curve calculated for conductor temperature of 20 degrees Celsius.

Outputs

R (T_C): Denotes resistance calculated at the conductor temperature (T_C) in °C.

Step by Step Procedure

Step 1: Consider steady state heat balance equation defined in chapter 2 section(2.3), writing all terms Q_C, Q_R, Q_S as function of conductor temperature (T_C).

$$Q_C = (0.0019(D * (\frac{v}{\mu_F})^{0.6}) * K_F * K_{ANGLE} * (T_C - T_A))$$

$$Q_R = 0.0178 * D * \in * (\frac{T_C + 273}{100})^4 - (\frac{T_A + 273}{100})^4$$

$$Q_S = \alpha * A_S * \sin(\vartheta)$$

It is noted that Q_S does not depend on conductor temperature.

Re-writing Q_C and Q_R in terms of conductor temperature (T_C) we get the equations as

$$(0.0019(D * \left(\frac{v}{\mu_f}\right)^{0.6} * K_F * K_{ANGLE} * (T_C - T_A))) + (0.0178 * D * \epsilon * \left(\frac{T_C+273}{100}\right)^4 - \left(\frac{T_A+273}{100}\right)^4) = Q_S + I^2 r(T_0)[1 + \alpha(TC - T_0)$$

The above equation represents a re-arranged heat balance equation where all the terms are written as function of conductor temperature (T_C)

Step 2: Given wind speed (v) in m/s calculate conductor temperature (T_C) and find the corresponding resistance R (T_C) of the transmission line.

Procedure described above is applicable for modeling any weather dependent transmission lines. The analysis is not confined to voltage stability analysis as it can be applied to short circuit analysis, load flow analysis etc

Next section describes a way to incorporate non-uniformities of wind speeds along the transmission line using a line model segmentation procedure, explained with the help of a flow chart [32]. Figure 4.3 represents an example *N*-segment transmission line model, in which each segment is characterized by a different wind speed (v_1, v_2, … , v_N) and corresponding conductor temperature (T_{C1}, T_{C2}, … , T_{CN}).

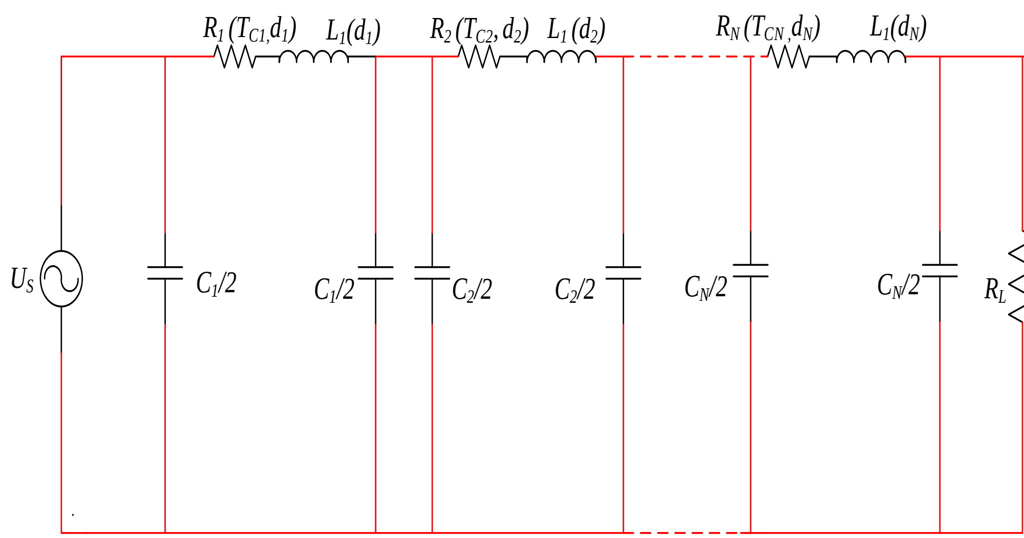

FIGURE 4.3: N-segment line model with each line segment modeled at a specific wind speed (v_{C1}, v_{C2}, … , v_{CN}), each segment resistance is dependent on corresponding conductor temperature ($R(T_{C1})$, $R(T_{C2})$, … , $R(T_{CN})$), inductance ($L_1(d_1)$, $L_2(d_2)$, …, $L_N(d_N)$) and capacitance ($C_1/2$, $C_2/2$, … , $C_N/2$) are independent of wind speed but depend on segment length, the load resistance is indicated by R_L.

4.2.2. From Wind Speed Profile to Multi-Segment Line Model

The flow chart explaining the line model segmentation procedure based on a given wind speed profile is shown in figure 4.4 and results in appropriate line model segmentation, i.e. number of segments and each segment length, to include conductor temperature non-uniformities and then calculate each segment parameter values.

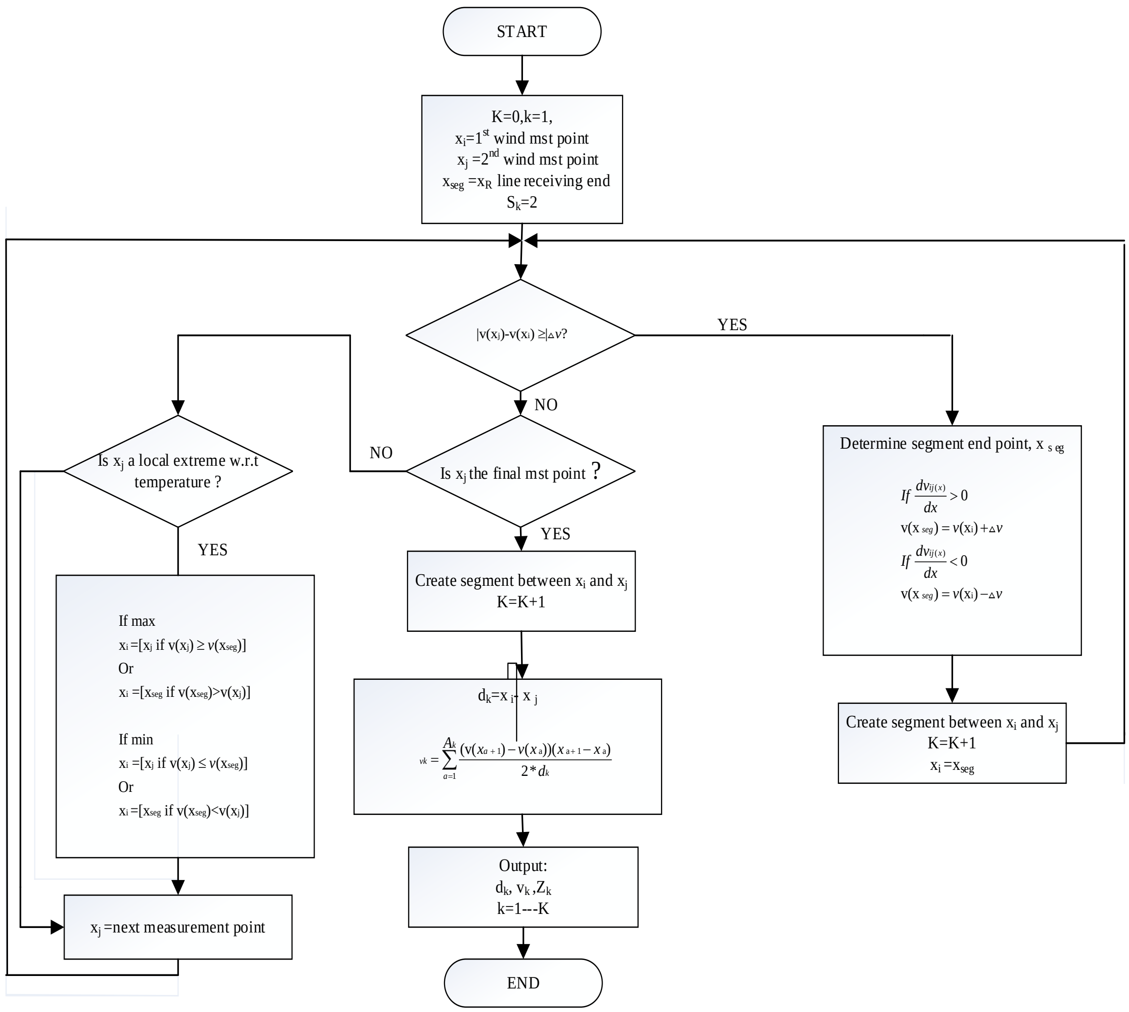

FIGURE 4.4: Flow chart representation showing algorithm for performing line model segmentation based on wind speed measurements

Where:

K: Total number of segments

x_i, x_j: Wind measurement points for line segmentation

x_{seg}: Segment end location

k: Segment number

d_k: length of segment k

S_k: Number of points used to calculate segment wind speed v_k (beginning and end points +number of measurement points located within segment k)

Z_k: Series impedance

v_k: segment wind speed as weighted average.

Transmission line modeled with single line segment for one wind measurement:

For representation purposes, figure 4.5 shows a transmission line modeled for a single value of wind speed for the entire line length.

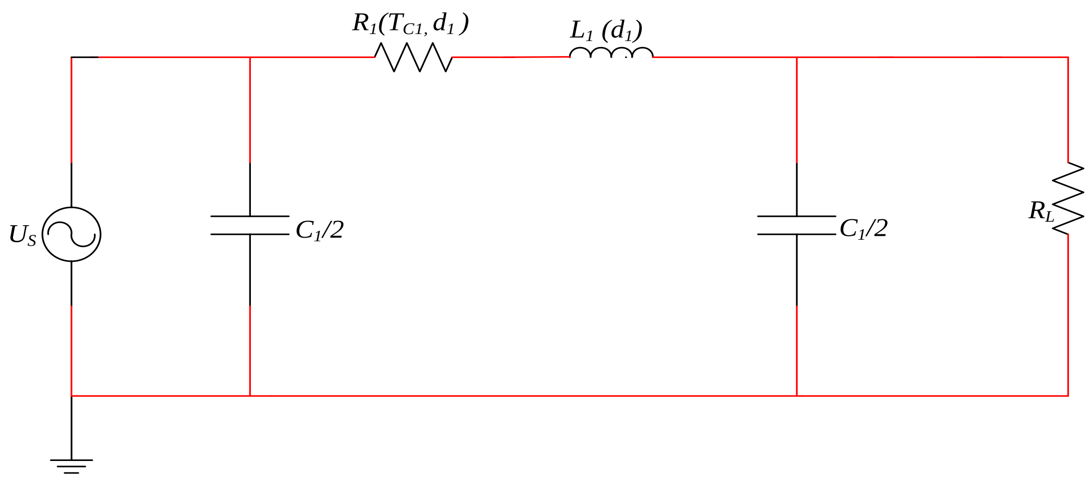

FIGURE 4.5: (π) Line model with single line segment having sending end voltage(U_S), resistance of line dependent on conductor temperature (T_{C1}),with inductance (L_1), capacitance divided in two halves ($C_1/2$), ($C_1/2$), load resistance (R_L).

From the figure 4.5

U_S: Sending end voltage of the transmission line in kilo Volts (kV)

R_1 (T_{C1}): Line segment resistance (R_1) calculated at conductor temperature (T_{C1}) in ohms (Ω)

L_1: Inductance of the transmission line in milli-Henry (mH)

$C_1/2$: Represents half of total capacitance of the line in micro- Farad (µF)

R_L: Load resistance represented in ohmic value (Ω).

d_1: Line length.

The model as shown in figure 4.5 can account for different wind speeds, but not for changes (i.e. gradients) in wind speed along the line. Assuming a higher wind speed ($v_2 > v_1$), conductor temperature would decrease ($T_{C2} < T_{C1}$) due the wind cooling effect, and line resistance would decrease ($R_2 < R_1$) resulting in an increased in allowable current flow through the transmission line. The one drawback about this single-segment model is that it could not take into account a change in wind speed along the line.

Block diagram representation of Multi-segment lumped parameter line model to include non-uniformities of wind speed along the line

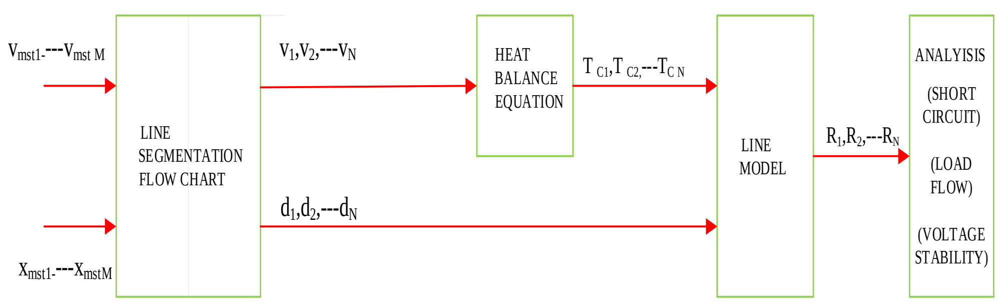

FIGURE 4.6: Proposed modeling approach with wind speed measurement inputs: measurement value ($v_{mst1}, v_{mst2}, \ldots, v_{mstM}$) and measurement location ($x_{mst1}, x_{mst2}, \ldots, x_{mstM}$), resulting line model segmentation: segment lengths and conductor temperatures ($d_1, d_2, \ldots, d_N, T_{C1}, T_{C2}, \ldots, T_{CN}$), and resulting resistance of each segment ($R_1, R_2, \ldots, R_N$).

From figure (4.6)

Inputs

v_{mst1}, v_{mst2}---v_{mstM} : Wind speed measurements along the transmission line in m/s

v_1, v_2---v_N : Wind speeds of line segments in m/s

x_{mst1}, x_{mst2}---x_{mstM} : Line distance measurements along the transmission line in (kms)

d_1, d_2---d_n: Length of line segments in (kms)

T_{C1}, T_{C2}, T_{CN} : Segment conductor temperatures in (°C)

R_1, R_2, R_N: Resistances calculated at corresponding conductor temperatures in (°C)

Outputs

Once the model is determined, all system level analysis can be carried out as it is done traditionally (e.g. load flow, short circuit analysis, voltage stability).

Next section describes the line modeling procedure for a given wind speed profile determined from two available wind speed measurements along the length of the transmission line. Transmission line of length is divided into multiple segments S_1, S_2, S_3--S_n with length of line segments $d_1 = d_2 =$ - - - - - - d_n and wind speeds ($v_1 \neq v_2 \neq$-------v_N) in each line segment.

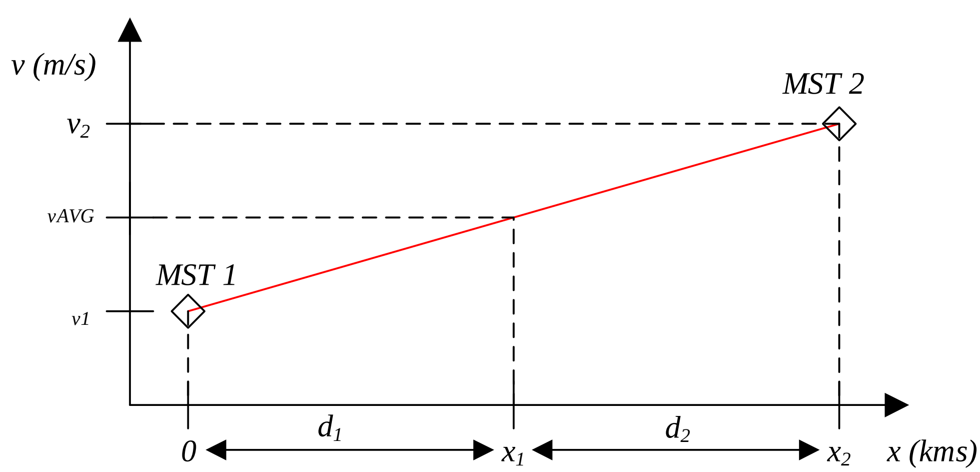

FIGURE 4.7: Representation of wind profile v dependent on distance x

In figure 4.7, a wind speed profile along the 200 km line is determined given two assumed measurements: v_1 at the beginning (x = 0) and v_2 at the end of the line (x = 200 km). A monotonic increase of wind speed is assumed. The line could be modeled by using a single lumped parameter segment with resistance calculated at the conductor temperature resulting, for example, from a simple average wind speed value of v_{avg}. Alternatively, a multi-segment line model can be used to better represent the wind speed profile. As an example, the line is divided into two line segments each of which is 100 km long. The resistance of the first line segment was calculated for the average wind speed from the first half of the line and the second line segment for the second half of the line. The resulting circuit representation of this 2-segment line model is shown in figure 4.8.

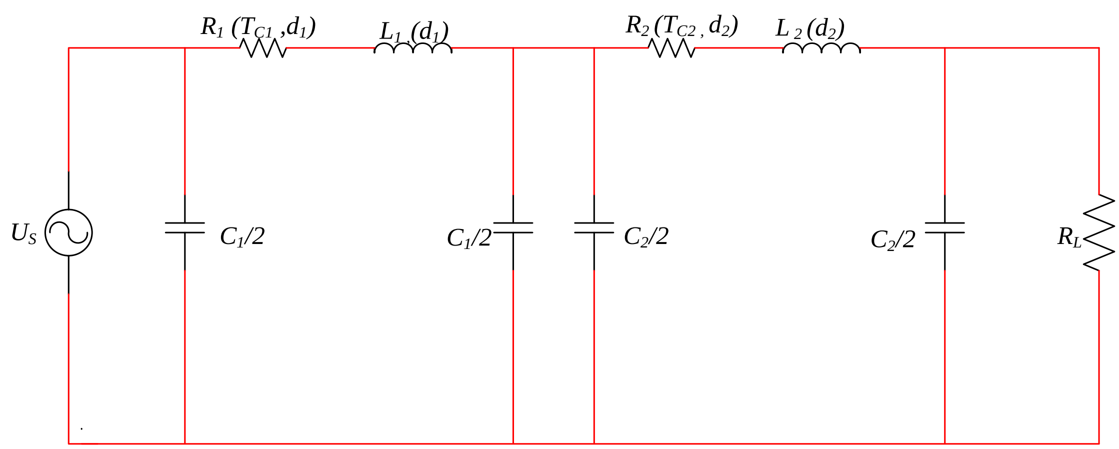

FIGURE 4.8: 2-segment line model with each line segment modeled at wind speed (v_{avg1} and v_{avg2}) respectively, resistances calculated at corresponding conductor temperatures $R(T_{C1})$ and $R(T_{C2})$, inductances ($L_1(d_1)$ and $L_2(d_2)$) and capacitances ($C_1/2$ and $C_2/2$), sending-end voltage (U_S) and load resistance (R_L).

The figure (4.8) shows diagrammatic representation of two lumped (π) line segments. The two line segments are of equal length and are modeled at their own average wind speeds and corresponding resistance values are calculated at corresponding conductor temperatures.

U_S: Sending end voltage of transmission line in kilovolts (kV).

R_1 ($T_{C1,}$ d_1): Resistance of first line segment in ohms (Ω) calculated at conductor temperature (T_{C1}) for wind speed (v_1) in m/s.

R_2 ($T_{C2,}$ d_2): Resistance of second line segment in ohms (Ω), calculated at conductor temperature (T_{C2}) for wind speed (v_2) in m/s.

L_1 (d_1),L_2 (d_2): Both halves of inductances in milli-henry (mH), constitute the total inductance of transmission line.

$C_1/2$,$C_2/2$: Capacitance of line (μf) divided into 4 equal sections in order to keep total capacitance of line equal for complete section of transmission line.

R_L: Load is modeled as constant impedance (resistive load) calculated in ohms (Ω).

The motive of the study is to comprehend significance of non-uniformities of wind speeds when incorporated in modeling transmission lines. Given varying geographical and weather conditions it may be advantageous to include non-uniformities in wind speeds to model transmission line. The following case study presented includes non-uniformities of both wind speeds and line model segment length.

A wind speed profile which is monotonically changing with wind speed and distance along the transmission line is considered in this study [18].Transmission line model is divided into multiple lumped parameter line segments with each line segment parameter values modeled at corresponding wind speed of line segment and is of different length. Depending on weather and geographical conditions, transmission line segment parameter values change accordingly and can be calculated by the equation.

$$Z(T_C(d)) = R(T_C(d)) + j * X_L(d)$$

Where,

$Z(T_C(d))$ = Impedance, function of distance and conductor temperature.

$R(T_C(d))$ = Resistance dependent on conductor temperature and segment length

$X_L(d)$ = Inductive reactance independent with wind speed and conductor temperature but function of segment length d.

An example wind speed profile is shown in figure 4.9 and gives an example transmission line model characterized by three non-uniform segments with each line segment parameter values calculated at its own wind speed and length.

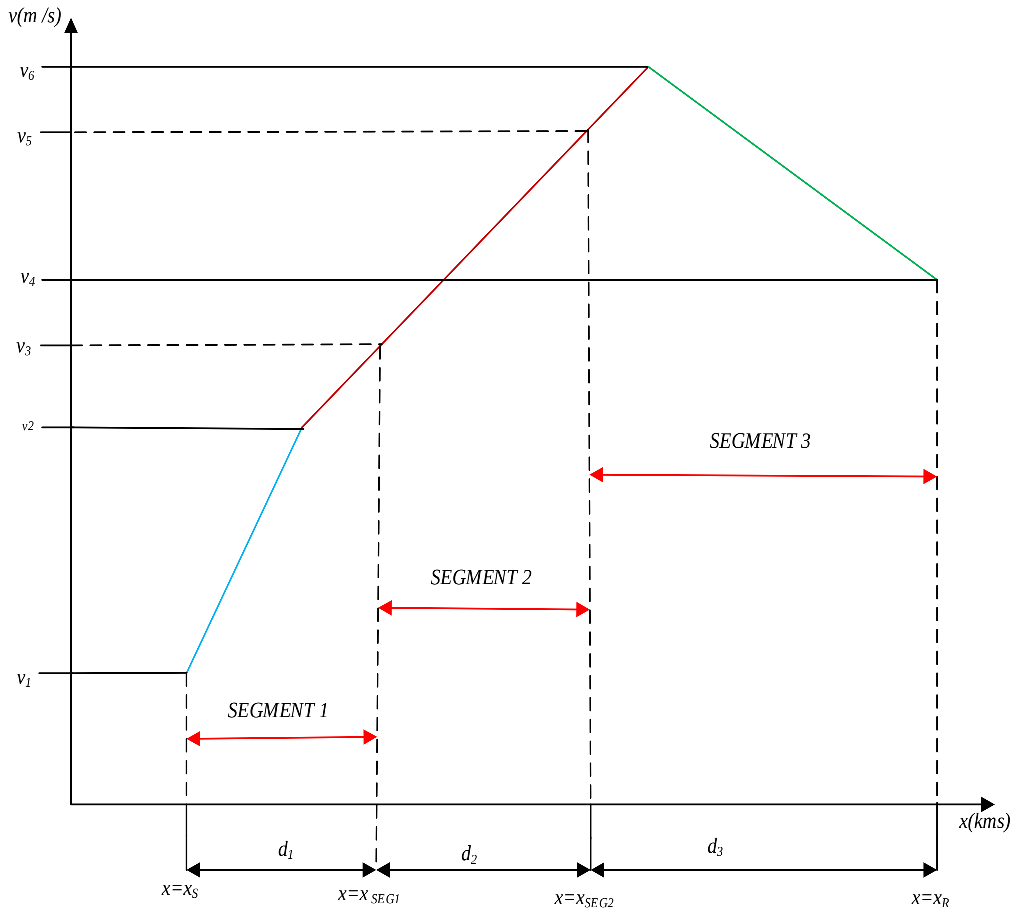

FIGURE 4.9: Wind profile v(x) v/s Position(x) plotted along the line based on wind speed measurements obtained along length of transmission line.

A 3- segmented non-uniform line model dependent on wind speed and distance (x) is presented in figure 4.9. First line segment(S_1) is modeled at segment wind speed (v_{S1}) in m/s and distance (d_1) in kms .Similarly second line segment (S_2) modeled at wind speed (v_{S2}) in m/s and distance (d_2)in kms and third line segment (S_3) at wind speed (v_{S3}) and distance (d_3) in kms with ($v_{S1} \neq v_{S2} \neq v_{S3}$)and ($d_1 \neq d_2 \neq d_3$).

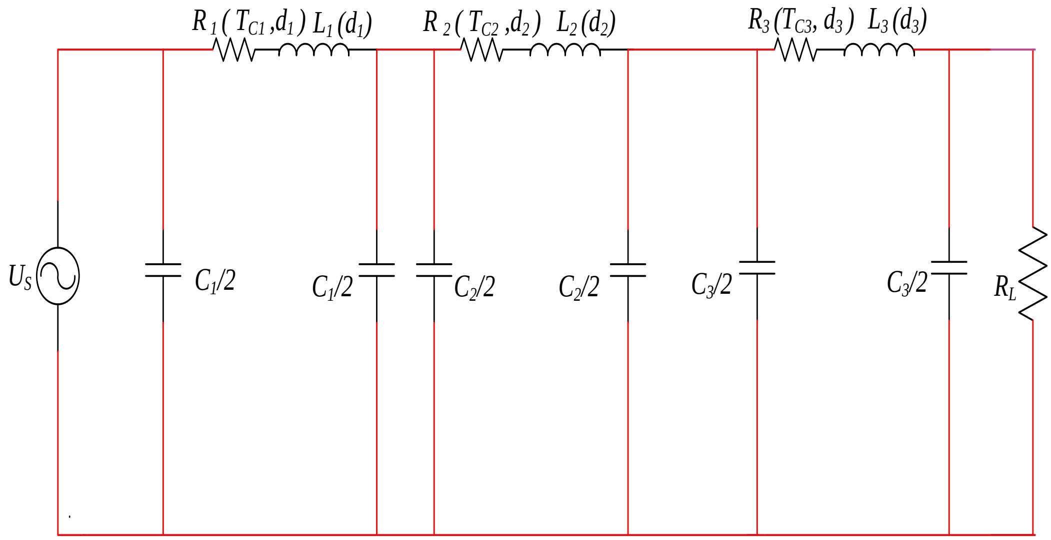

FIGURE 4.10: 3-segment line model with each line segment modeled at wind speeds (v_{C1}, v_{C2}, v_{C3}) and corresponding resistances calculated at conductor temperatures $R_1(T_{C1},d_1)$, $R_2(T_{C2},d_2)$, $R_3(T_C,d_3)$, inductances ($L_1(d_1)$), ($L_2(d_2)$), ($L_3(d_3)$), capacitances ($C_1/2$, $C_2/2$, $C_3/2$), sending-end voltage (U_S) and resistive load (R_L).

U_S: Sending end voltage of line in kilo-volts (kV).

$R_1(T_{C1},d_1)$:Resistance of first line segment in ohms (Ω) calculated at conductor temperature (T_{C1}) for wind speed (v_{s1}) in m/s.

$R_2(T_{C2},d_2)$: Resistance of second line segment in ohms (Ω) calculated at conductor temperature (T_{C2}) for wind speed (v_{s2}) in m/s.

$R_3(T_{C3},d3)$: Resistance of third line segment in ohms (Ω) calculated at conductor temperature (T_{C3}) for wind speed (v_{s3}) in m/s.

L_1 (d_1), L_2 (d_2), L_3 (d_3): Inductances in milli-Henry (mH) divided for 3 segments which constitute the total inductance of transmission line

$C_1/2$,$C_2/2$,$C_3/2$: Capacitance of line (µf) divided into 6 sections in order to keep total capacitance of line equal for complete section of transmission line.

R_L: Load modeled as constant impedance (resistive load) in ohms (Ω).

It may be more advantageous to include non-uniformities of wind speeds and length while modeling line segment parameter values. Given that ambient conditions are never same throughout the transmission line, adopting this methodology may result in better accuracy and performance of transmission line as it represents more realistic conditions.

4.3. Determining Line Power Handling Capabilities

The proposed method for modeling transmission line parameters and the line model developed in section 4.2.1 can be applied to any of the power system applications. From section 4.2.1 once new resistance of transmission line R (T_C) is known it can be used for any system level analysis like,

- Load flow analysis
- Voltage stability –PV (Power vs Voltage) curves
- Short Circuit analysis
- State estimation
- Economic Dispatch

This thesis focus will be on obtaining voltage stability curves to get better estimates of ampacity (maximum allowable current) and power handling capabilities of transmission line.

Once the sending end voltage(U_S),line parameters calculated at conductor temperature (T_C) and load modeled as constant impedance (resistive load)(R_L) in ohms(Ω) are known then calculate current flowing through transmission line (I) in amperes, receiving end voltage (U_R), maximum power handling capabilities of transmission line. For particular load value (R_L) a single node in the voltage stability curve (power vs voltage (PV)) can be obtained.

For different load values and wind speeds, note corresponding new resistance line values and currents flowing through transmission line (I).

Finally, calculate receiving end voltage (U_R,) and maximum power transfer capabilities of transmission line. Joining all node points obtained for different load values we get complete voltage stability (PV) curve.

The maximum power transfer capabilities are usually determined by the “nose” of the PV curve obtained [29].

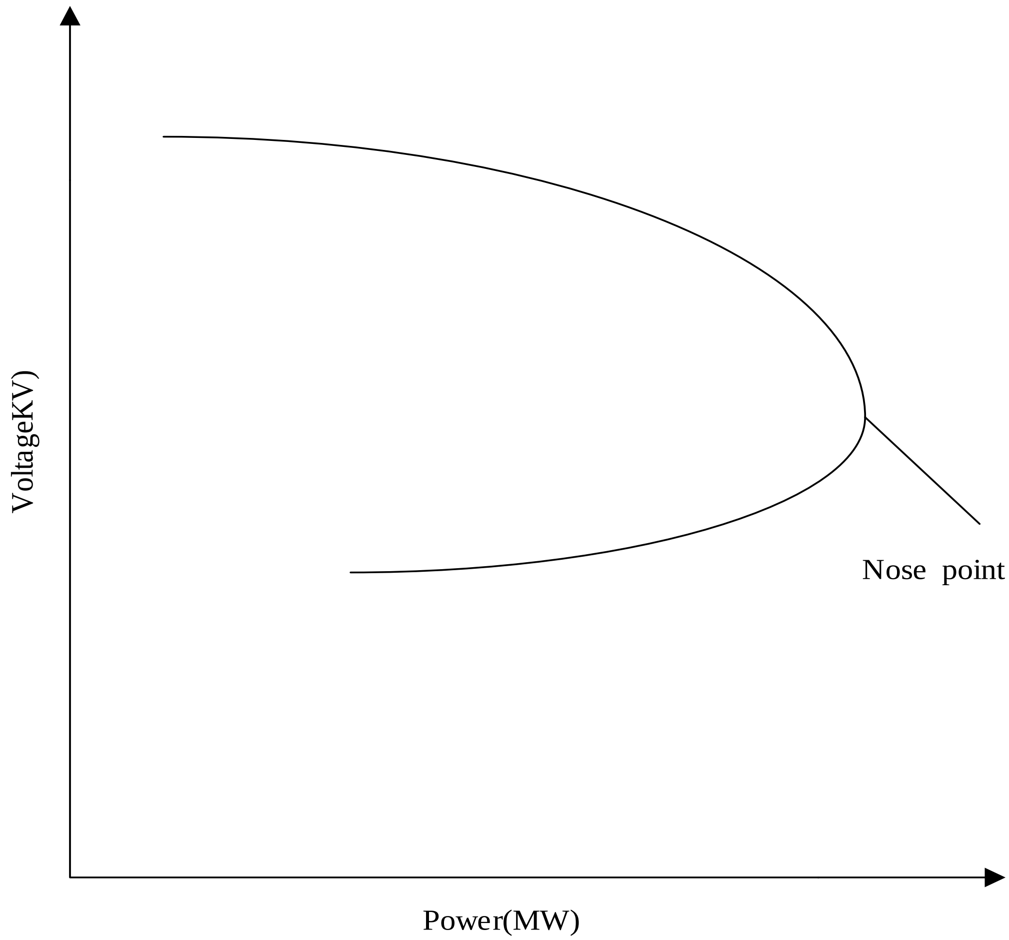

FIGURE 4.11: A simple PV curve with its nose point [29]

The simulation results pertaining to the test case studies presented in chapter 5 consider voltage stability curves for analyzing estimates of power handling capabilities of transmission lines.

CHAPTER 5 : SIMULATION RESULTS

5.1. Overview

Chapter 5 presents simulation results for test cases .Section 5.2 introduces test case transmission line parameter values required for line modeling. Effects of conductor temperatures on transmission line ampacity and maximum power handling capabilities for transmission line are described in section 5.3. Section 5.4 focus on studying impact of different wind speeds in transmission line modeling. Section 5.4.1 presents the comparison of thermal and voltage stability limits and explains the limiting factor among the two. Section 5.5 explains impact of changes in wind speed along the length of the transmission line on transmission line parameters. Sub-section 5.5.1and 5.5.2 presents wind profiles that include non-uniformities of wind speed and length while calculating transmission line parameter values. Section 5.6 provides the summary of test cases and observations.

5.2. Test Case Line Parameters

For demonstration purposes a Drake conductor is used and hypothetical medium length line of 200 kms is considered. The test case line parameter values are shown in table 5.1 which are considered from [15] .In order to assess effects of wind speed along the line and calculate maximum power handling capabilities and ampacity of transmission line voltage stability analysis is considered. PV (power vs voltage) curves are used as metrics. The following case studies are examined in this thesis.

Case 1

- Effect of conductor temperature on ampacity and maximum power capabilities of transmission line

Case 2

- Effects of wind speed on transmission line model parameters.

    1. Comparison of voltage stability and thermal limits

Case 3

- Effects of changes in wind speed along the length of the transmission line

    2. Multi-segment lumped parameter line models (uniform model segmentation)

Case 4

- Effects of changes in wind speed along the length of the transmission line

    3. Multi-segment lumped parameter line models (non-uniform model segmentation)

The following table demonstrates per unit length line parameter values that are considered for modeling the 200 km transmission line.

TABLE 5.1: Test Case Line Parameters

L	200 kms
$R(T_O)$	0.1172 Ω/mile
U_S	169.705 kV
X_C	0.0912 MΩ-mile
X_L	0.399 Ω/mile

5.3. Effects of Conductor Temperature

Case 1

This section explains impact of conductor temperature on selected power system metrics like receiving end voltage, maximum allowable current and maximum power transferred through transmission line. As resistance is function of conductor temperature it is necessary that we need to get better estimate of the conductor temperature. Incorporating wind speed in the line modeling will help in getting better estimate of conductor temperature conductor because of cooling effects of wind speed. The 200kms transmission line is modeled for two conductor temperatures of 20 degrees Celsius and 50 degrees Celsius respectively. Simulation results of PV curves (Power vs Voltage) obtained are shown in figure 5.1.

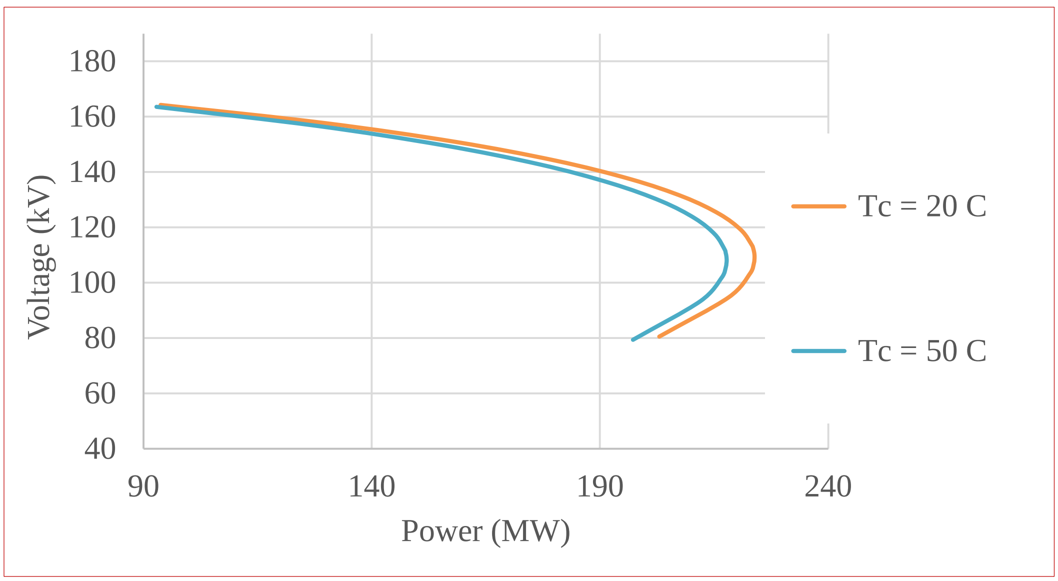

FIGURE 5.1: PV (voltage (kV) v/s power (MW)) curves for two conductor temperatures (T_C=20 and 50 °C)

The PV curves in figure 5.1 indicate that maximum power point decreases as the conductor temperature increases. At 20 °C the P_{max} is 223.89 MW and for 50 °C its 218

MW nearly indicating that maximum power dropped due to decrease in the conductor temperature. Beyond, P_{max} system loses its voltage stability and becomes unstable.

TABLE 5.2: Table showing Resistance, Inductance and Capacitance values for 20°C and 50°C

T_C(°C)	R(Ω)	L(mH)	C(μF)
20	14.56	131	3.61
50	15.96	131	3.61

As mentioned in the modeling assumptions in chapter 3 (section 3.3) changes in line parameters due to conductor temperature or wind speed will only impact the resistance of the transmission line. Table 5.3 presents values of voltages, currents, and power values at 20°C and 50°C.

TABLE 5.3: Voltage, Current, Power values at two different conductor temperatures at 20°C and 50°C

	Temperature at 20 °c			*Temperature at 50 °c*	
Voltage (kV)	*Current(Amp)*	*Power(MW)*	*Voltage (kV)*	*Current(Amp)*	*Power(MW)*
U_{LOAD}(kV)	I_{LOAD}(Amp)	P_{LOAD}(MW)	U_{LOAD}(kV)	I_{LOAD}(Amp)	P_{LOAD} (MW)
164.29	570.476	93.724	163.51	567.75	92.832
157.74	821.589	129.6	156.67	816.0505	127.85
150.95	1048.31	158.24	149.67	1039.4	155.58
144.13	1251.107	180.32	142.71	1238.589	176.88
137.42	1431.64	196.74	135.92	1416.05	192.47
130.96	1591.49	208.42	129.42	1572.6	203.52
124.77	1733.178	216.25	123.21	1711.4	210.88
118.92	1858.456	221.01	117.37	1834.198	215.28
113.43	1969.24	223.36	111.9	1942.65	217.39
112.37	1989.667	223.6	110.7	1962.3	217.59
111.32	2010.012	223.76	109.81	1982.6	217.71
110.29	2029.685	223.86	108.7	2001.96	217.78
109.27	2048.94	223.89	107.77	2020.84	217.79
108.27	2067.664	223.86	106.78	2039.18	217.72
107.28	2085.985	223.78	105.88	2057.162	217.64
103.44	2155.386	222.95	101.98	2125.2	216.75
94.7	2303.2	218.22	93.4	2270.24	212.05
80.5	2519.14	203.01	79.436	2483.188	197.26

From the results obtained in table 5.3 it is evident that for lower conductor temperature of 20°C better estimates of ampacity and power handling capabilities of transmission line are possible.

Next, section 5.4 discuss impacts of considering different wind speeds on line parameter values resistance, inductance and capacitance.

5.4. Effects of Wind Speed

Case 2

A 200 kms transmission line is considered. Different wind speeds (5, 10, 25 m/s) are incorporated for modeling 200 kms transmission line. Corresponding conductor temperatures and resistances calculated for wind speeds are shown in tables 5.4 and 5.5.Transmission line was modeled depending on resistance value obtained for each wind speed and corresponding temperature. The following figures show block diagram representation of transmission line modeled for single value of wind measurement for complete length of transmission line.

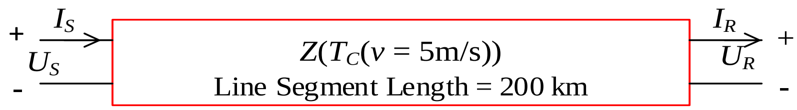

FIGURE 5.2: Block diagram for single line segment modeled at wind speed of 5m/s with sending end voltage (U_S), sending end current (I_S),receiving end current(I_R) of line.

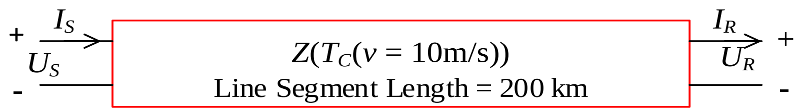

FIGURE 5.3: Block diagram for single line segment modeled at wind speed of 10m/s with sending end voltage (U_S),sending end current(I_S),receiving end current(I_R) of line.

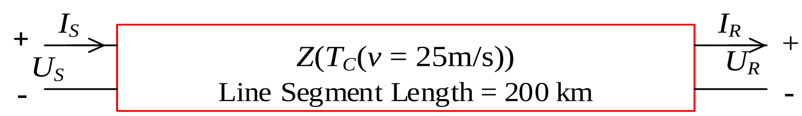

FIGURE 5.4: Block diagram for single line segment modeled at wind speed of 25m/s with sending end voltage (U_S),sending end current(I_S),receiving end current(I_R) of line.

Voltage stability (PV) curves acquired for different wind speeds when incorporated in modeling transmission line parameters are shown in figure 5.5.

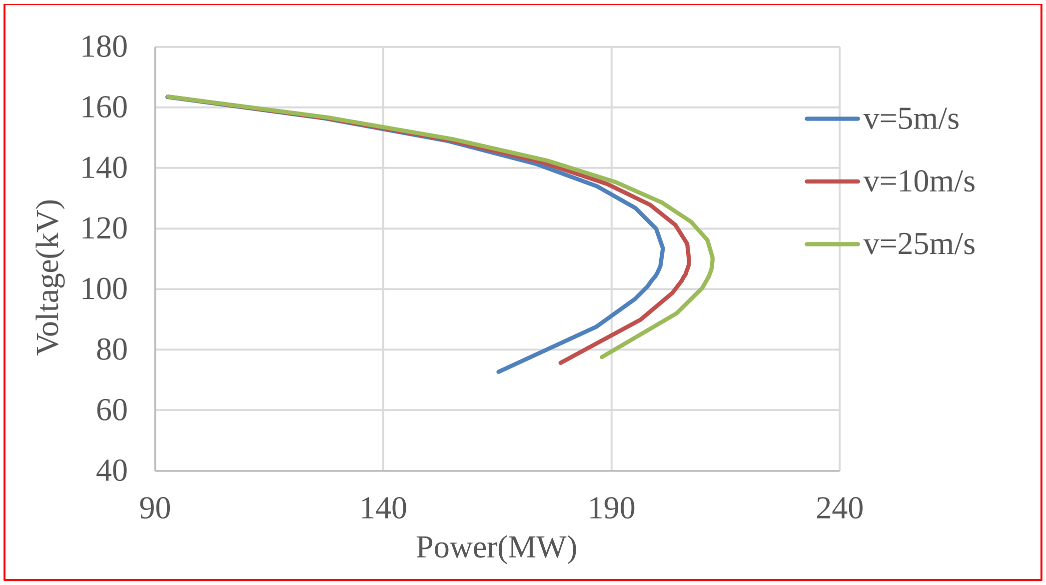

FIGURE 5.5: PV (voltage (kV) v/s power (MW)) curves for different wind speeds (v=5, 10, 25m/s)

From figure 5.5 the curves indicate that when different wind speeds are considered for modeling transmission line parameter values we obtain better estimates of maximum power handling capabilities and ampacity for transmission lines for lines which are modeled for higher wind speeds.

TABLE 5.4: Comparison of voltages for wind speeds (5, 10, 25 m/s)

v_1=5m/s	v_2=10m/s	v_3=25m/s
U_{LOAD}(kV)	U_{LOAD}(kV)	U_{LOAD}(kV)
163.42	163.5	163.57
156.33	156.51	156.66
148.92	149.22	149.52
141.35	141.92	142.37
133.92	134.71	135.36
126.75	127.78	128.62
119.92	121.19	122.22
113.49	114.99	116.17
107.51	109.21	110.53
106.36	108.09	109.45
105.22	106.99	108.38
104.11	105.91	107.32
103.11	104.87	106.28
101.93	103.81	105.26
100.87	102.77	104.25
96.77	98.791	100.35
87.62	89.878	91.983
72.7	75.636	77.52

Table 5.4 shows comparison of load voltages for different wind speeds .It is evident that if the wind speed profile is of increasing nature as seen in figures (5.2, 5.3, and 5.4) then better estimates of voltages are possible. This may be an important outcome since it helps in understanding voltage profile for power system. Commenting on voltage stability, it is seen that incorporating ambient conditions, such as wind speed, in transmission line models can provide a better estimate of maximum allowable power. Given grid vulnerability, sudden and continuous changes in load, wind speed dependent transmission line modeling gives a better way of modeling transmission line parameter values.

Table 5.5 indicates that with increase in wind speed the temperature of the conductor decreases. As the conductor temperature decreases the resistance of the line decreases. This will result in better estimate of maximum allowable current in the transmission line. From table 5.6 maximum current carrying in conductor (ampacity) for transmission line occurs when line operates at wind speed of 25 m/s and for wind speed of 5 m/s it is least. Thus cooling effects play a crucial role in changing the maximum current carrying capacity of transmission line.

TABLE 5.5: Comparison of conductor temperatures and resistances calculated for wind speeds (5, 10, 25 m/s)

	Wind Speeds (v_1,v_2,v_3 in m/s)							
	v_1=5	v_2=10	v_3=25	v_1=5	v_2=10	v_3=25		
R_{LOAD}(Ω)	T_{C1}(°C)	T_{C2}(°C)	T_{C3}(°C)	R_1(Ω)	R_2(Ω)	R_3(Ω)	L(mH)	C(μF)
287.99	48.3318	45.5872	43.2915	16.12	15.974	15.848	131	3.61
191.99	54.354	49.5724	45.5968	16.46	16.18	15.976	131	3.61
143.99	61.964	54.5534	48.4414	16.8	16.46	16.132	131	3.61
115.199	70.3605	59.9959	51.5265	17.34	16.76	16.3044	131	3.61
95.99	80.3423	66.304	55.0209	17.88	17.12	16.4976	131	3.61
82.285	90.4321	72.6088	58.475	18.44	17.46	16.688	131	3.61
71.99	100.794	78.9858	61.9173	19.02	17.82	16.8792	131	3.61
63.99	111.201	85.2994	65.2764	19.6	18.172	17.064	131	3.61
57.599	121.481	91.45	68.5063	20.16	18.512	17.2436	131	3.61
56.47	123.496	92.6528	69.1299	20.28	18.578	17.278	131	3.61
55.384	125.527	93.8589	69.7569	20.398	18.646	17.312	131	3.61
54.339	127.553	95.0562	70.3763	20.5	18.712	17.3472	131	3.61
53.33	129.563	96.2391	70.9888	20.62	18.76	17.38	131	3.61
52.363	131.534	97.3896	71.589	20.73	18.84	17.414	131	3.61
51.428	133.509	98.5673	72.1864	20.82	18.906	17.4472	131	3.61
47.99	141.32	103.141	74.5222	21.26	19.1596	17.576	131	3.61
41.142	159.67	113.75	79.8615	22.28	19.746	17.86	131	3.61
31.99	191.262	131.71	88.6553	24.62	20.74	18.34	131	3.61

TABLE 5.6: Comparison of currents flowing in transmission lines for different wind speeds (5, 10,25m/s) when modeled at different resistive load values

	v_1=5m/s	v_2=10m/s	v_3=25m/s
R_{Load}	I_{LOAD}(Amp)	I_{LOAD}(Amp)	I_{LOAD}(Amp)
287.99	567.44	567.72	567.96
191.99	814.11	815.185	815.99
143.99	1034.26	1036.3	1038.4
115.199	1227	1231.96	1235.85
95.99	1395.11	1403.32	1410.12
82.285	1540.38	1553.02	1563.1
71.99	1665.73	1683.45	1697.53
63.99	1773.54	1796.92	1815.44
57.599	1866.53	1895.7	1919.88
56.47	1883.39	1914.1	1938.05
55.384	1899.8	1931.84	1956.84
54.339	1916.01	1949.14	1975.22
53.33	1931.48	1966.4	1992.95
52.363	1946.53	1982.47	2010.24
51.428	1961.6	1998.41	2027.2
47.99	2016.5	2058.57	2091.18
41.142	2129.71	2184.59	2220.74
31.99	2272.61	2364.35	2418.9

TABLE 5.7: Comparison of power for wind speeds at (5, 10,25m/s)

v_1=5m/s	v_2=10m/s	v_3=25m/s
P_{LOAD}(MW)	P_{LOAD}(MW)	P_{LOAD}(MW)
92.731	92.823	92.903
127.24	127.55	127.83
154.03	154.65	155.26
173.44	174.84	175.96
186.82	189.03	190.87
195.24	198.46	201.04
199.75	204.01	207.45
201.28	206.61	210.99
200.67	207.01	212.09
200.31	206.91	212.12
199.98	206.69	212.08
199.48	206.44	211.97
198.95	206.21	211.83
198.41	205.75	211.55
197.89	205.39	211.34
195.15	203.37	209.87
186.661	196.35	204.27
165.22	178.82	187.85

A better estimate of power handling capabilities of transmission line can be achieved by modeling line parameters dependent on wind speed. From the table 5.7 the maximum power obtained is P_{max}=214.02 MW at v_3=25 m/s and for v_1=5m/s the transmission line cannot handle more than 200.67 MW.

Next section gives a comparison of voltage stability limits and thermal limits. Thermal limits are calculated at maximum allowable conductor temperature of 100 degrees Celsius (explained in chapter 2 section (2.3)) and voltage stability limits calculated for tables considered in (5.3 and 5.7).

5.4.1. Comparison of Thermal and Stability Limits

TABLE 5.8: Comparison of thermal and stability limits for wind speeds (5, 10,25m/s)

	Thermal Limits at $(T_{Cmax})=100°C$	*Stability Limits*			*Limiting factor*
Wind Speed v(m/s)	I_{max} *(amps)*	P_{Max} *(MW)*	*I (amps)* at P_{Max}	T_C *at* P_{Max}	
5	1723	200	1866	121	Thermal
10	2108	207	1896	91	Stability
25	2760	212	1938	69	Stability

The table 5.8 presents comparison of thermal and stability limit values calculated. For wind speed of 5m/s limiting factor is thermal limit because maximum allowable current for thermal limit would be 1723 amperes which is less than stability limit value. In case of wind speeds of 10m/s and 25m/s stability limit is considered as limiting factor because maximum allowable conductor current (ampacity) for thermal limit is 2108 and 2760 amperes respectively which is considered to be higher than stability limit current values.

5.5. Effects of Changes in Wind Speed Along the Length of Transmission Line

Case 3

- Multi-segment lumped parameter line models (uniform model segmentation)

5.5.1. Wind Speed Profile 1

In figure 5.6 a wind profile along the 200 km line is assumed. Two wind speed measurements are taken into account. At the beginning of the line x = 0 the wind speed is 5 m/s and at the end of the line its 55 m/s. A monotonic increase of wind speed is assumed. At first the line is modeled by using a single lumped parameter segment with resistance calculated at the conductor temperature resulting from simple average wind speed of 30 m/s. Then, a two-segment line model was used to better represent the wind speed profile. In the two-segment model, the line is divided in two uniform (i.e. equal length) segments each 100 km long. The resistance of the first segment was calculated for the average wind speed from the first half of the line and the second segment for the second half of the line. The resulting PV curves are shown in figure 5.9.

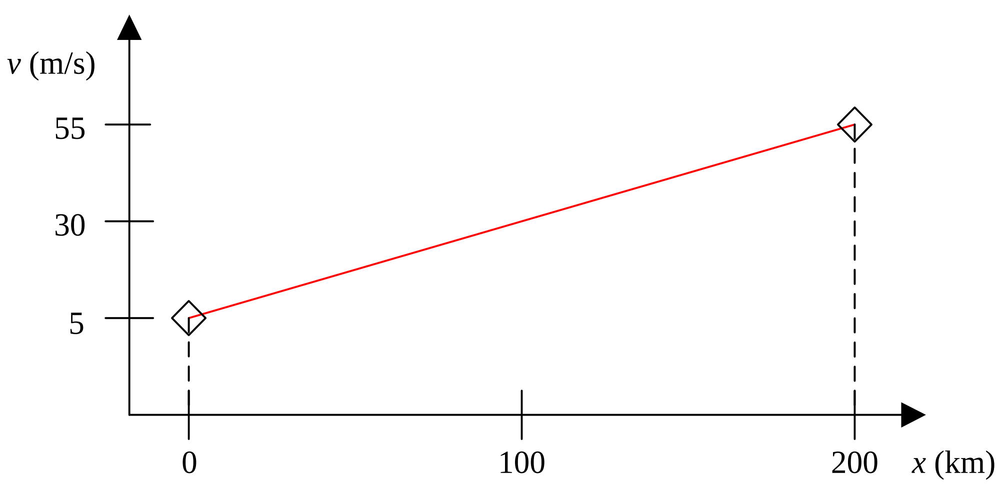

FIGURE 5.6: Graphical representation of example wind profile and two possible ways to incorporate wind speed information within the line model.

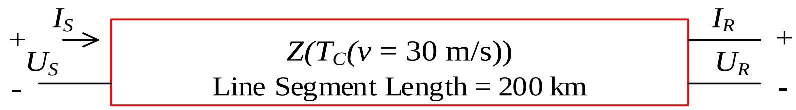

FIGURE 5.7: Block diagram for single line segment modeled at average wind speed of 30m/s with sending end voltage(U_S),sending end current(I_S),receiving end current(I_R) of line.

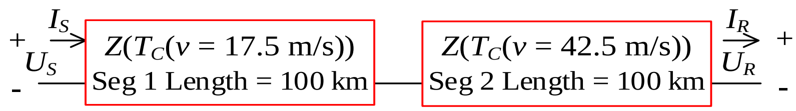

FIGURE 5.8: Block diagram for two line segments, each segment modeled at average wind speed of (17.5m/s) and (42.5m/s) with sending end voltage (U_S), sending end current (I_S), receiving end current (I_R) of line

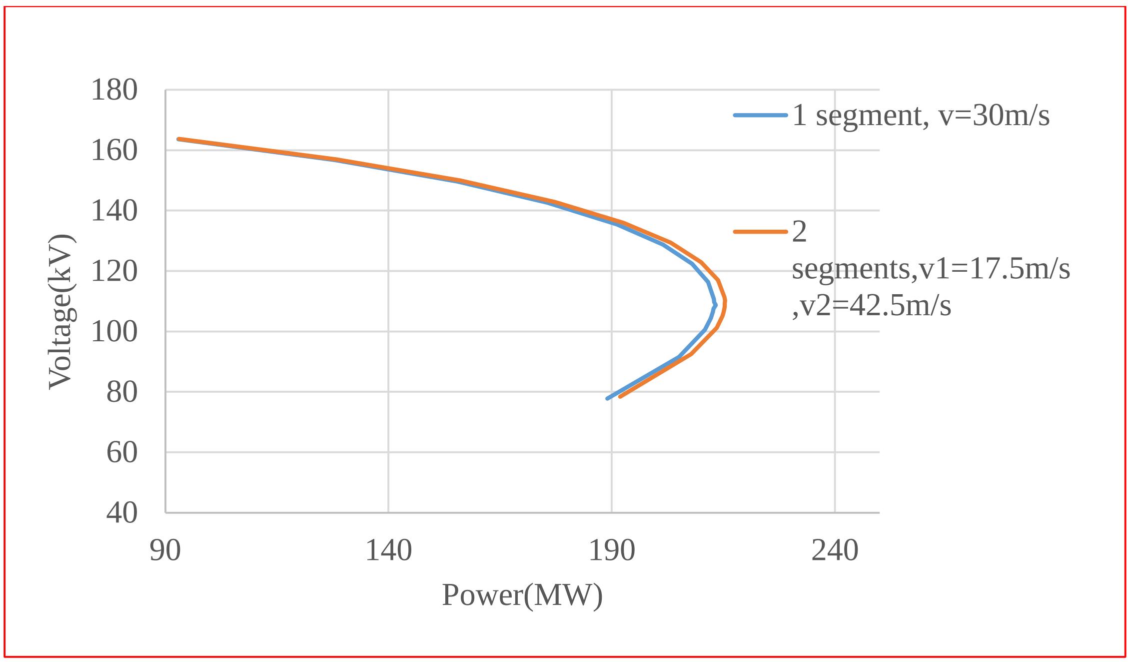

FIGURE 5.9: PV curves for line segments operated at their average wind speeds

TABLE 5.9: Table showing the conductor temperature and line parameter values (resistance, inductance and capacitance) for line modeled at 30 m/s.

Entire line segment modeled for wind speed of (v=30m/s)			
T_C(°C)	R_{LINE}(Ω)	L(mH)	C(µF)
42.9408	15.814	131	3.61
45.0057	15.928	131	3.61
47.5502	16.07	131	3.61
50.3064	16.2228	131	3.61
53.4174	16.395	131	3.61
56.4876	16.564	131	3.61
59.5405	16.7338	131	3.61
62.5131	16.8982	131	3.61
65.3655	17.056	131	3.61
65.9155	17.0864	131	3.61
66.4684	17.0116	131	3.61
67.0143	17.146	131	3.61
67.5539	17.176	131	3.61
68.0826	17.206	131	3.61
68.6085	17.2354	131	3.61
70.6629	17.348	131	3.61
75.3481	17.608	131	3.61
83.0315	18.032	131	3.61

The line parameter values and conductor temperature values for line modeled at v=30m/s is shown in table 5.9.The resistance of the transmission line is alone subjected to change with change in wind speed via conductor temperature. The inductances and capacitances values are assumed to be non-changeable with changes in wind speed or conductor temperature.

TABLE 5.10: Comparison of conductor temperatures, line resistances, inductances and capacitances values for line divided into two line segments and modeled at corresponding average wind speeds in each of the line segments.

First line segment modeled at wind speed of(v_1= 17.5m/s) Second line segment modeled at wind speed of(v_2= 42.5m/s					
T_{C1}(°C)	T_{C2}(°C)	R_{LINE1}(Ω)	R_{LINE2}()	$L_{1/2}$(mH)	C(μF)
44.0598	42.395	7.945	7.899	65.5	0.902
46.9142	44.07	8.0246	7.945	65.5	0.902
50.4504	46.145	8.12246	8.003	65.5	0.902
54.2968	48.356	8.22	8.064	65.5	0.902
58.6872	50.8549	8.35	8.133	65.5	0.902
63.0062	53.2922	8.4569	8.201	65.5	0.902
67.4059	55.7496	8.59	8.269	65.5	0.902
71.6841	58.113	8.709	8.3344	65.5	0.902
75.7546	60.3374	8.822	8.395	65.5	0.902
76.6174	60.844	8.846	8.409	65.5	0.902
77.4223	61.2461	8.868	8.421	65.5	0.902
78.2187	61.6746	8.89	8.432	65.5	0.902
79.0067	62.1021	8.914	8.444	65.5	0.902
79.7792	62.5193	8.933	8.456	65.5	0.902
80.549	62.9339	8.954	8.4677	65.5	0.902
83.5646	64.5502	9.028	8.5124	65.5	0.902
90.4968	68.2247	9.23	8.614	65.5	0.902
102.023	74.2073	9.54	8.7795	65.5	0.902

From table 5.10 it is evident that the line is divided into two segments in which each line segment is modeled at its own average wind speed .It can be observed that conductor temperature of first line segment will be on higher side than for second line segment .Similarly the resistance value for second line segment is less than the resistance for first line segment.

When non-uniformities of wind speeds are included in modeling transmission lines, then the probability for better performance of decision making tools is high. This is because when real data of ambient conditions like wind speed non-uniformities are included in modeling transmission line parameters then better estimate of ampacity (maximum allowable current) and line power handling capabilities of transmission line are possible.

TABLE 5.11: Comparison of voltage, currents, powers values for line modeled with single segment avg wind speed(30m/s) and for line divided into two segments modeled at their corresponding average wind speeds(17.5m/s and 42.5m/s)

Voltage (kV)	*Current(amp)*	*Power (MW)*	*Voltage (kV)*	*Current(Amp)*	*Power (MW)*
U_{LOAD}*(kV)*	I_{LOAD}*(amp)*	P_{LOAD}*(MW)*	U_{LOAD}*(kV)*	I_{LOAD}*(Amp)*	P_{LOAD}*(MW)*
163.59	568.036	92.924	163.72	568.493	93.074
156.7	816.1725	127.95	156.94	817.442	128.29
149.58	1038.805	155.38	149.92	1041.192	156.1
142.68	1230.14	175.52	142.89	1240.395	177.24
135.46	1411.24	191.17	135.96	1416.45	192.58
128.75	1564.6	201.46	129.33	1571.5	203.18
122.36	1699.716	207.98	122.95	1707.84	209.97
116.35	1818.22	211.55	116.96	1827.71	213.76
110.72	1922.37	212.86	111.35	1933.19	215.26
109.65	1941.688	212.9	110.27	1952.674	215.34
108.69	1962.532	213.31	109.21	1971.6	215.32
107.53	1978.937	212.8	108.16	1990.4	215.28
106.5	1996.916	212.66	107.12	2000.58	215.15
105.48	2014.345	212.46	106.11	2026.3	215
104.47	2031.41	212.23	105.1	2043.992	214.78
100.58	2095.88	210.82	101.22	2109.15	213.49
91.487	2232.42	205.04	92.46	2247.35	207.79
77.765	2430.918	189.04	78.341	2448.915	191.85

For single segment modeled at average wind speed of 30m/s maximum power is 213.31 MW and for line modeled with two segments it is 215.32 MW. This is an indicative of the importance of not only including wind speed in line modeling approach but also representing wind speed non-uniformities along length of transmission line. Considering varying geographic and weather conditions while modeling transmission line parameter values may prove to be significant.

Next section explains a wind speed profile that considers non-uniformities of both wind speeds and length in resistance, inductance, and capacitance values.

5.5.2. Wind Speed Profile 2

Case 4

The figure 5.10 shows a wind profile for 200 kms long transmission line drawn based on wind measurements obtained in Alaska [34]. Based on wind measurements obtained from four weather stations the 200 kms transmission line is divided into 3 non-uniform line segments based on line segmentation procedure explained. It can be observed that each line segment is modeled at different wind speed and having different line length. The line parameter values for each line segment are then calculated at corresponding conductor temperature of the line segment.

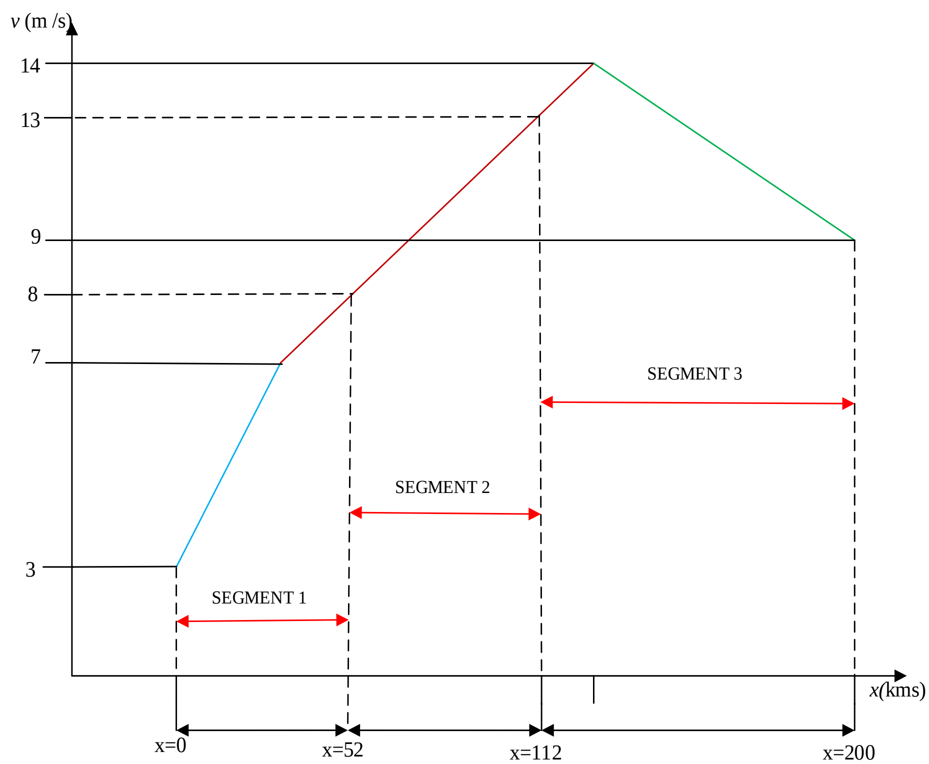

FIGURE 5.10: Wind profile v in (m/s) v/s Position (x) in kms plotted based on wind speed measurements measured along length of transmission line in Alaska.

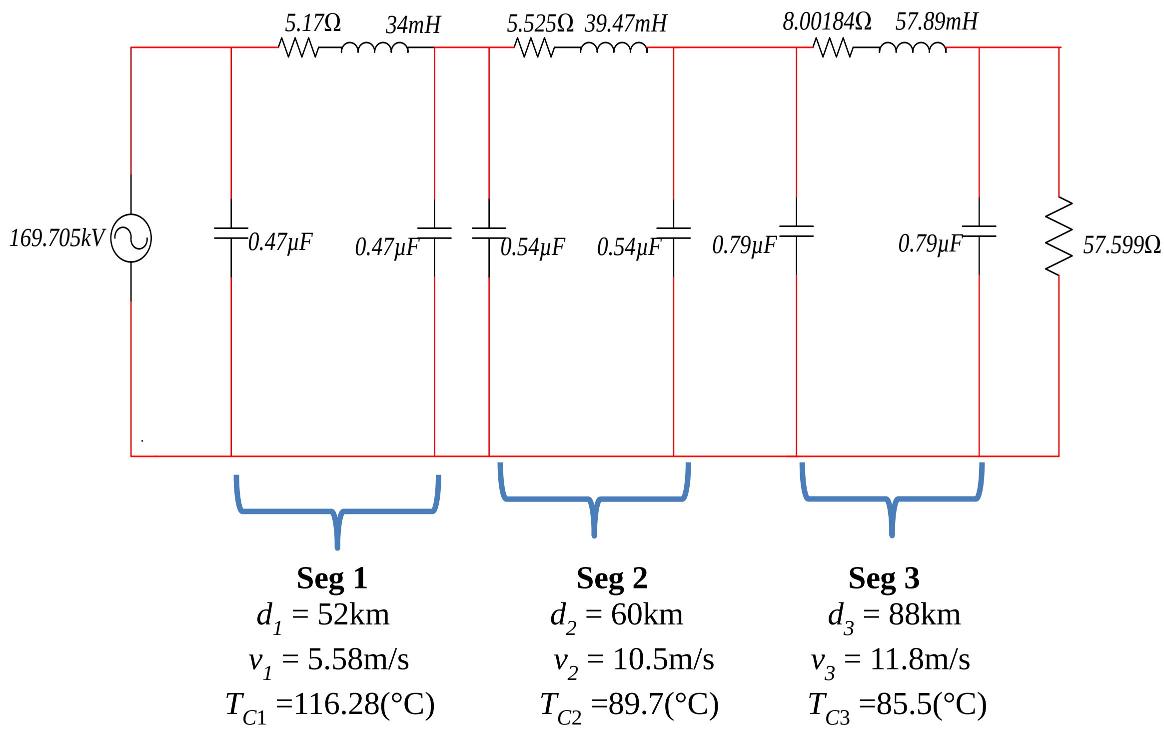

FIGURE 5.11: Representation of 3 non-uniform segmented transmission line

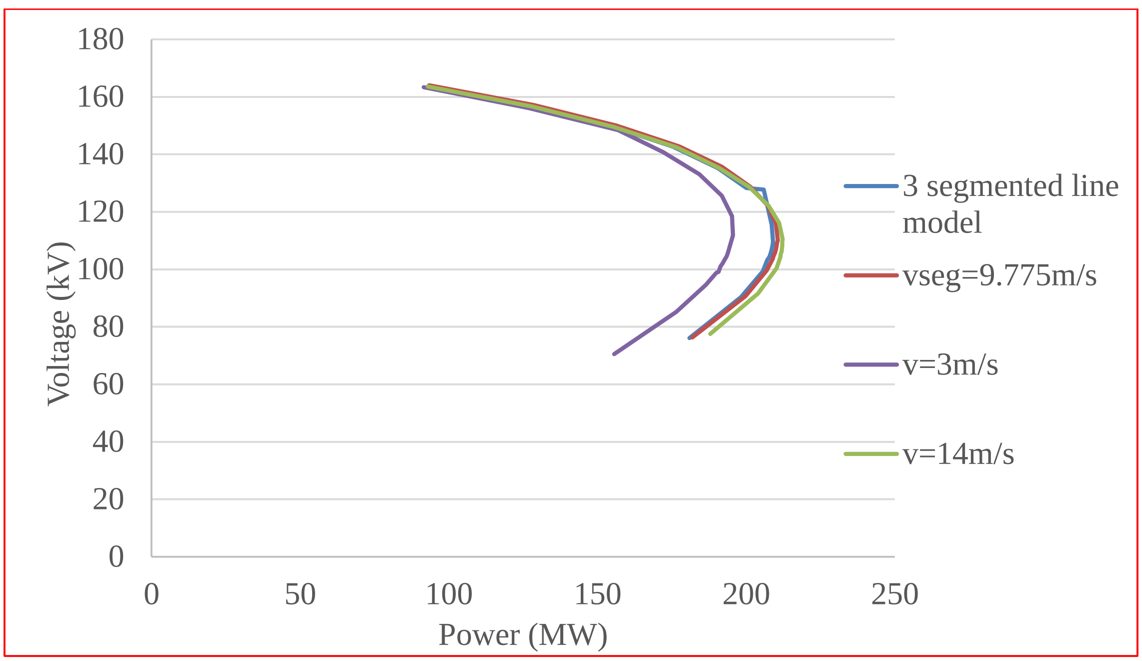

FIGURE 5.12: Voltage stability curves (voltage (kV) v/s power (MW)) graph drawn for line divided into 3-non-uniform segments, highest and lowest wind measurements and wind speed at weighted average

Resistance will be lower for line segment operating at higher wind speed or for lowest conductor temperature. From figure 5.10 the transmission line starts at x = 0, ends at x = 200 km with length of first line segment at d_1 = 52 km operating wind speed of 5.58 m/s. Second line segment at d_2 = 60 km for wind speed of 10.5 m/s and third line segment modeled for d_3 = 88 km and at wind speed of 11.8 m/s. Voltage stability (PV) curve for the line modeled based on wind profile considered is shown in figure (5.12). PV curve indicate that better estimates of power handling capabilities and ampacity of transmission line are possible. Maximum power for the 3-segment line model obtained for this case study is 209.03 MW.

TABLE 5.12: Comparison of conductor temperatures and line resistances for line divided into 3 line segments each operating at different wind speeds (5.58, 10.5, 11.8m/s) respectively with unequal lengths in each line segment (d_1=52kms, d_2=60kms, d_3=88kms)

Segment length (d_1)=52KM	*Segment length (d_2)=60KM*	*Segment length (d_3)=88KM*	*Segment length (d_1)=52KM*	*Segment length (d_2)=60KM*	*Segment length (d_3)=88KM*
T_{C1}(°c)	T_{C2}(°c)	T_{C3}(°c)	R_{SEG1} (Ω)	R_{SEG2} (Ω)	R_{SEG3} (Ω)
47.8927	45.45	45.03	4.186	4.7904	7.0153
53.5776	49.3209	48.61	4.264	4.8546	7.102
60.7628	54.1566	53.06	4.371	4.932	7.21
68.6721	59.4376	57.9258	4.482	5.022	7.329
78.257	65.5426	63.5206	4.622	5.118	7.465
87.4955	71.6571	69.1133	4.756	5.22	7.602
97.1651	77.8172	74.73	4.893	5.32	7.738
106.885	83.92	80.29	5.03	5.4288	7.8733
116.281	89.7494	85.57	5.17	5.525	8.00184
118.345	91.0311	86.74	5.2	5.546	8.03038
120.23	92.1936	87.79	5.227	5.562	8.0564
122.104	93.342	88.83	5.254	5.584	8.08192
123.97	94.49	89.8771	5.28	5.604	8.1065
125.816	95.615	90.895	5.307	5.622	8.1312
127.65	96.7357	91.909	5.33	5.6412	8.156
134.91	101.175	95.89	5.438	5.724	8.245
151.93	111.3	105.11	5.6784	5.88	8.479
180.994	128.52	120.52	6.10116	6.168	8.852

TABLE 5.13: Voltage, currents, powers for line divided into three line segments with, each line segment operating at wind speeds (5.58,10.5,11.8m/s),respectively and with unequal length in line segment

$U_{LOAD}(kV)$	$I_{LOAD}(Amp)$	$P_{LOAD}(MW)$
163.71	568.46	93.064
156.82	816.8	128.09
149.52	1038	155.27
142.62	1229.62	175.34
135.21	1408.2	190.47
128.32	1559.3	200.09
127.73	1690.6	205.85
115.52	1805	208.56
109.72	1903	209.03
108.61	1923.3	208.87
107.51	1940.5	208.7
106.43	1958.63	208.42
105.36	1975.5	208.14
104.31	1992.04	207.79
103.27	2008	207.04
99.271	2060	205.53
90.32	2192	198.27
76.05	2377.65	180.85

From table 5.13 the maximum power handling capability of the transmission line is considered to be 209.03 MW. Based on the voltage stability analysis if the stability limit goes beyond 209.03 MW then system goes into the instability mode which may not be desirable condition.

TABLE 5.14: Conductor temperatures, line resistances, receiving end line voltages, currents, power handling capabilities of transmission line calculated for wind speed of $v_{avg=}$9.975m/s

T_C (°C)	R_{LINE}(Ω)	V_{SOURCE}(kV)	V_{LOAD}(kV)	I_{LOAD}(Amp)	P_{LOAD}(MW)	R_{LOAD}
45.7035	15.072	169	164	569	93.4	287.99
49.749	15.296	169	157.18	818	128.68	191.99
54.8	15.56	169	150.004	1041	156.34	143.99
60.32	15.88	169	142.8	1239	177.4	115.199
66.73	16.236	169	135.63	1413	191.84	95.99
73.146	16.592	169	128.73	1564	201.37	82.285
79.62	16.94	169	122.14	1696	207.22	71.99
86.0531	17.3	169	115.92	1811	209.97	63.99
91.65	17.6	169	110.15	1912	210.65	57.599
93.53	17.718	169	108.95	1929	210.33	56.47
94.7664	17.786	169	107.88	1947	210.14	55.384
95.98	17.84	169	106.81	1965	209.95	54.339
97.1935	17.922	169	105.72	1982	209.59	53.33
98.37	17.986	169	104.68	1999	209.25	52.363
99.56	18.052	169	103.64	2015	208.85	51.428
104.22	18.308	169	99.628	2076	206.83	47.99
115.03	18.9	169	90.65	2203	199.74	41.142
133.33	19.92	169	76.27	2384	181.821	31.99

Table 5.14 presents the line parameter values calculated for line modeled at weighted average of wind speed of 9.975 m/s, obtained for the wind profile shown in figure 5.10. The maximum power handling capability for this transmission line and this wind speed conditions is 210.65 MW. The maximum power transfer point occurs at a voltage of 110.15 kV. After the nose point, the voltage collapses and system goes into the instability region.

TABLE 5.15: Conductor temperatures, line resistances, receiving end line voltages, currents, power handling capabilities of transmission line calculated for wind speed of v=14m/s

T_C (°C)	R_{LINE}(Ω)	V_{SOURCE}(kV)	V_{LOAD}(kV)	I_{LOAD}(Amp)	P_{LOAD}(MW)	R_{LOAD}
43.27	15.84	169	163.57	567.97	92.9	287.99
45.577	15.96	169	156.65	816	127.84	191.99
48.4221	16.12	169	149.53	1038	155.4	143.99
51.5071	16.23	169	142.45	1236	176.6	115.199
55.0012	16.48	169	135.35	1410	190.8	95.99
58.4551	16.68	169	128.62	1562	201.05	82.285
61.897	16.86	169	122.23	1697	207.5	71.99
65.256	17.04	169	116.2	1815	210.99	63.99
68.48	17.22	169	110.55	1919	212.19	57.599
69.1093	17.268	169	109.45	1938	212.15	56.47
69.7363	17.3	169	108.39	1956	212.12	55.384
70.3557	17.3376	169	107.33	1975	221.01	54.339
70.9681	17.36	169	106.3	1993	211.9	53.33
71.56	17.404	169	105.26	2010	211.6	52.363
71.63	17.408	169	104.29	2027	211.5	51.428
73.45	17.508	169	100.41	2092	210.15	47.99
79.84	17.86	169	91.6	2226	203.9	41.142
88.63	18.34	169	77.52	2423	187.86	31.99

Table 5.15 presents the line parameter values for line modeled at a wind speed of 14 m/s which is the highest measurement of the given wind profile, as shown in figure 5.10. The maximum power handling capability for these wind conditions is 212.19 MW, occurring at a corresponding voltage of 110.55 kV, after which the voltage collapses and the system goes into the instability region.

TABLE 5.16: Conductor temperatures, line resistances, receiving end line voltages, currents, power handling capabilities of transmission line calculated for wind speed of v=3m/s

T_C(°C)	R_{LINE}(Ω)	V_{SOURCE}(kV)	V_{LOAD}(kV)	I_{LOAD}(Amp)	P_{LOAD}(MW)	R_{LOAD}
51.118	16.28	169	163.33	567.13	91.5	287.99
59.2521	16.736	169	156.1	813	126.7	191.99
69.6515	17.3	169	148.48	1031	156.9	143.99
81.2174	17.94	169	140.75	1220	172.1	115.199
95.255	18.72	169	133.05	1386	184.2	95.99
109.5721	19.52	169	125.62	1526	191.74	82.285
124.433	20.34	169	118.5	1645	195.19	71.99
139.48	21.18	169	111.87	1758	195.52	63.99
154.456	22.3	169	105.67	1834	193.82	57.599
157.398	22.16	169	104.49	1850	193.35	56.47
160.3609	22.32	169	103.32	1865	192.77	55.384
163.325	22.5	169	102.16	1879	192.05	54.339
166.26	22.66	169	101.02	1894	191.37	53.33
169.079	22.82	169	99.11	1908	190.63	52.363
172.032	22.98	169	98.81	1921	189.89	51.428
183.48	23.618	169	94.57	1970	186.39	47.99
210.26	25.1	169	85.19	2070	176.44	41.142
255.68	27.6	169	70.54	2205	155.55	31.99

Table 5.16 presents the line parameter values for the line modeled at a wind speed of 3 m/s, which is the lowest wind speed measurement for the given wind speed profile figure 5.10. The maximum power handling capability for this wind speed is 195.52 MW.

Hence, from the PV curves shown in figure 5.10 we can conclude that there are noticeable, quantifiable differences in estimated line maximum power handling capabilities based on the wind speed that is considered which modeling the transmission line.

5.6. Summary of Results and Observations

A unique method for modeling transmission lines that takes into account available wind speed information is presented in chapter 5. The importance and advantages of considering wind speed in line modeling is explained with help of test cases. Firstly, the effect of conductor temperature on the transmission line is studied. We could observe that as conductor temperature decreases, resistance of line value decreases and better estimate of power transfer capabilities and ampacity of transmission line are possible. Secondly, when the line parameters are calculated for different wind speeds, selected power system metrics like maximum power change based on the wind profile. The drawback is that non-uniformities of wind speed along the length of the line are not included while calculating transmission line parameters. To overcome the above drawback, a multi-segment lumped parameter line model structure is used to incorporate resulting non-uniformity in line parameters along the line. Better performance of decision making tools, such as state estimators, can be expected if more accurate line models are used to include variability in wind speed that affect transmission line performance. It may be more reliable and economical to model transmission lines including non-uniformities of line parameters due to wind speed variations.

CHAPTER 6 : CONCLUSIONS

6.1. Summary of Contributions

Significance of considering wind speed in modeling transmission lines, including line parameters (resistance, inductances and capacitances) and line model structure, was discussed in the thesis. A line modeling approach to include information of wind speed along transmission line was explained using steady state heat balance equation and the corresponding line parameters values were calculated based on wind speed and obtained conductor temperatures. A step by step procedure relating wind speed and resistance of line via conductor temperature was presented to obtain new line parameter values. Non-uniformities of wind speed and length were incorporated using multi-segment lumped parameter line models; in which each line segment was modeled at its own segment wind speed. Flow chart for line segmentation was presented in order to include non-uniformities of wind speeds. For analysis voltage stability (PV) curves were used as metrics to determine maximum power handling capabilities and ampacity of transmission line. Select test results show that incorporating wind speeds in line parameters will cool the conductor and give a better estimate of ampacity and line power handling capabilities. Taking into consideration of the difficulties associated with land space and cost, economically it may be more feasible for utilities to use a method such as the presented approach to achieve better estimates of the line power handling capabilities and maximum allowable currents (ampacity) for transmission lines.

6.2. Future Vision

A special investigation of change in line resistances due to wind speeds was the primary focus in this work. Modeling was done assuming that conductor temperature will effect only resistance of line but not inductances and capacitances. It will be compelling to analyze the impact of wind speeds on line inductances, capacitances. As transmission line consists of inductance, resistance and capacitance, conductor temperature of transmission line subjected to variations in magnetic and electric fields surrounding around the conductor should be examined as it will be interesting to observe the changes it brings to ampacity and maximum line power handling capabilities of transmission lines.

In addition, it will be interesting to study the line model approach developed for other system level studies like load flow analysis, short circuit analysis, economic dispatch etc

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APPENDIX A: SIMULATION SOFTWARE

Case 1: (π) Line model representation for single line segment in simulink

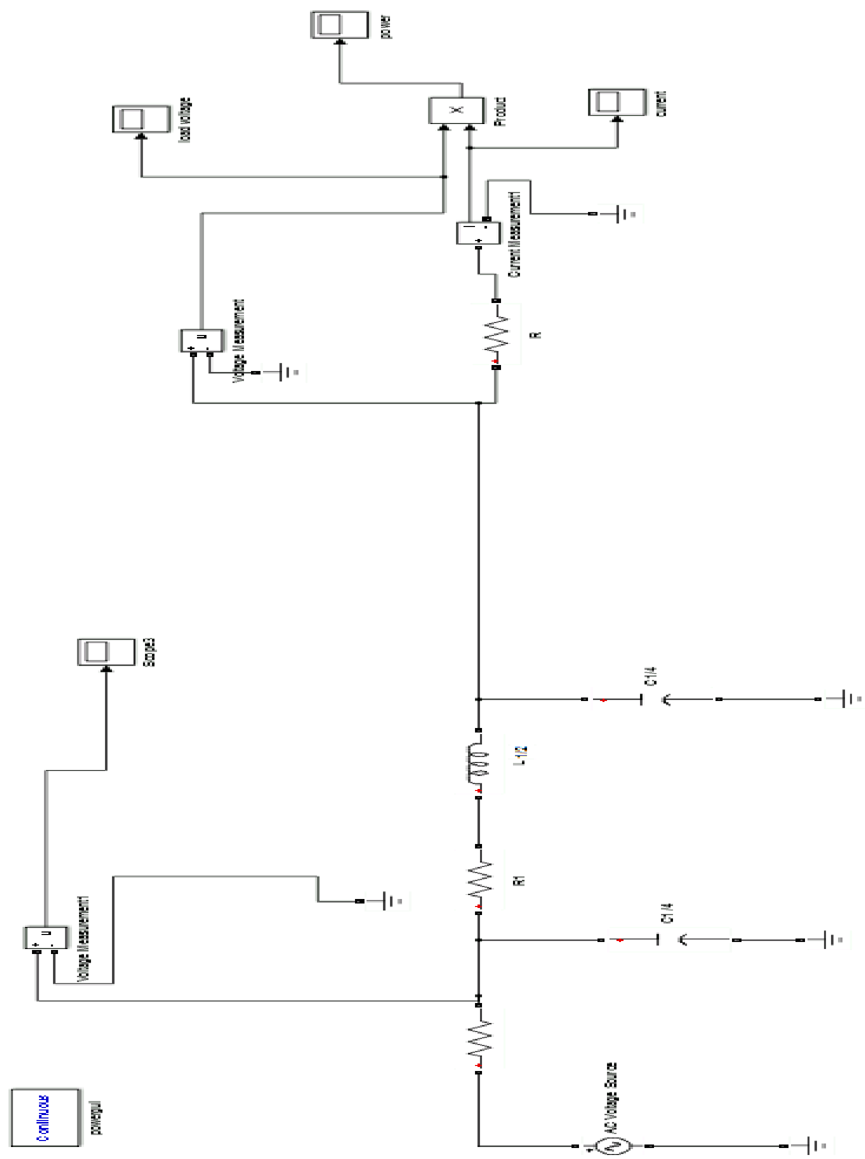

Figure 1: (π) Line model representation for single line segment in simulink

Case 2: (π) Line model representation for multiple uniform line segments in Simulink

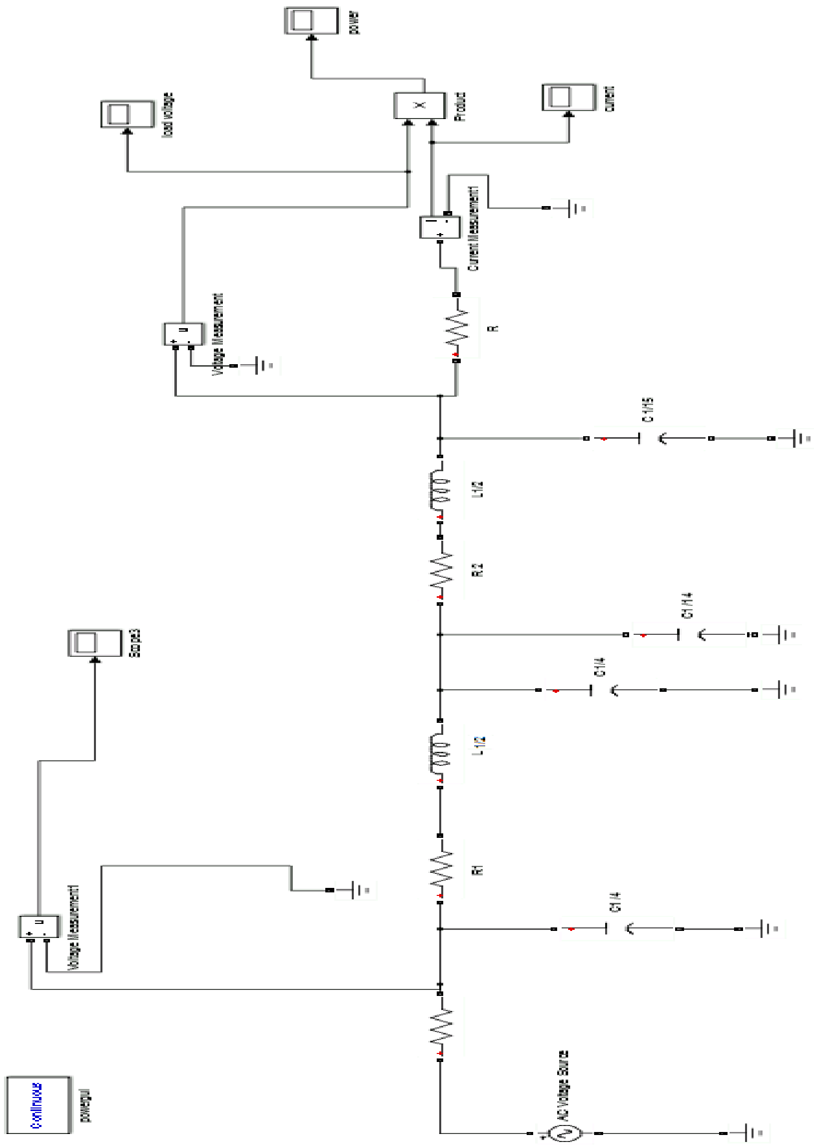

Figure 2: (π) line model representation for two uniform line segments in simulink

For modeling wind speed dependent transmission lines, Matlab/Simulink software was used. An AC voltage source (U_{ac}) is connected across the sending end of transmission Line.(π)Line model is connected between source voltages and receiving end. At receiving end, load (R_L) equal to the ohmic value (Ω) is connected. Figures (1) and (2) represents Matlab/Simulink representation for transmission line model with sending voltage being A.C source and load modeled as constant impedance (resistive load). For measuring voltage and current, voltmeter and ammeter are connected across the load. By obtaining voltage and current from meters, maximum power handling capability of transmission line and maximum allowable current through transmission line can be determined.