Exploring Six-Phase Transmission Lines for Increasing Power Transfer With Limited Right Of Way

by

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ABSTRACT

In the United States, especially in metropolitan areas, transmission infrastructure is congested due to a combination of increasing load demands, declining investment, and aging facilities. It is anticipated that significant investments will be required for new construction and upgrades in order to serve load demands. This thesis explores higher phase order systems, specifically, six-phase, as a means of increasing power transfer capability, and provides a comparison with conventional three-phase double circuit transmission lines.

In this thesis, the line parameters, electric and magnetic fields, and right of way are the criteria for comparing six-phase and three-phase double circuit lines. The calculations of the criteria were achieved by a program developed using MATLAB. This thesis also presents fault analysis and recommends suitable protection for six-phase transmission lines. This calculation was performed on 4-bus, 9-bus, and 118-bus systems from Powerworld® sample cases. The simulations were performed using Powerworld® and PSCAD®.

Line parameters calculations performed in this thesis show that line impedances in six-phase lines have a slight difference, compared to three-phase double circuit line. The shunt capacitance of compacted six phase line is twice of the value in the three-phase double circuit line. As a consequence, the compacted six-phase line provides higher surge impedance loadings.

The electric and magnetic fields calculations show that, ground level electric fields of the six-phase lines decline more rapidly as the distance from center of the lines increase. The six-phase lines have a better performance on ground level

magnetic field. Based on the electric and magnetic field results, right of way requirements for the six-phase lines and three-phase double circuit line were calculated. The calculation results of right of way show that six-phase lines provide higher power transfer capability with a given right of way.

Results from transmission line fault analysis, and protection study show that, fault types and protection system in six-phase lines are more complicated, compared to three-phase double circuit line. To clarify the concern about six-phase line protection, a six-phase line protection system was designed. Appropriate protection settings were determined for a six-phase line in the 4-bus system.

DEDICATION

To my wife and parents for their endless love.

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NOMENCLATURE

a	Three-phase operator
A_{wind}	Conductor area subjected to wind
B	Magnetic field density
B	Six-phase operator
C	Capacitance
CT	Current transformer
D_{kl}	Distances between conductor k and l
E	Voltage drop on a transmission line
$\tilde{E}$	Electric field strength vector
F_{total}	Total force on conductor due to wind force and conductor weight
F_{wind}	Wind force on conductor
f	Frequency
H	Magnetic field strength
I_{con}	Transmission line conductor current
I_{max}	Transmission line maximum load current
I_{phase}	Transmission line phase current
L	Transmission line inductance
M	Total number of transmission line overhead and image conductors

P	Transmission line active power transfer capacity
PSCAD	Power System Computer Aided Design
P_{wind}	Wind pressure on conductor
q_{con}	Charges on conductor
r_{con}	Transmission line conductor resistance
r_{ground}	Earth return conductor resistance
SIL	Surge impedance loading
V_{lg}	Transmission line phase-to-ground voltage
V_{ll}	Transmission line phase-to-phase voltage
V_{rated}	Transmission line rated phase-to-ground voltage
W_{cond}	Conductor weight
x	Transmission line reactance
Y	Transmission line admittance
Z	Transmission line impedance
$Z_a{}'$	Distance relay of Ground impedance
ε_0	Capacitance constant permittivity
Φ	Conductor flux linkage
μ_0	Inductance constant permeability
θ	Angle to the vertical axis
ρ	Earth resistivity

CHAPTER 1

INTRODUCTION

1.1 Background description

In United States, some states and regions have high demand load growth, due to the growth of the economy and the population. According to statistics from Arizona Public Service (APS), by 2008, the annual load demand growth rate for APS customers was approximately 5.3% in the last 20 years, and the estimated annual load demand growth rate will be 5% in the next 20 years [1]. In Texas, the estimated load demand of the ERCOT region will increase at an average rate of 2.5% from 1997 to 2015 [6]. The projected load growth rates in these areas are higher than the national average rate of 1.1 % [3]-[4]. The high load demand growth requires more power transfer capability of the existing transmission infrastructure. Considering the lengthy process of transmission line construction, investment on transmission grid should be made for the long term [5]. Additionally, the areas with high level load demands are suffering critical transmission grid congestion, because of the limited capacity of transmission infrastructure [6]. Southern California, Washington DC, Philadelphia, and New York are typical critical congestion areas. The congestion areas also demand additional transmission capability to deliver more power from neighboring areas [6].

In contrast to the continuing load demand growth and congestion, investments on new transmission facilities in the U.S. declined more than 44% over the past 25 years [7]-[8]. Meanwhile, most of the existing transmission infrastructures, which were constructed in 1950s, are aging. According to the data from Department of Energy (DOE), 70% of transmission lines and transformers are more than 25 years old and 60% of circuit breakers are more than 30 years old [8]. To meet the challenges on the transmission grid and improve power transfer capability, billions of dollars will be spent on new transmission infrastructure construction and upgrades [8].

The most common approach to increase power transfer capability is increasing system voltage. System voltage has been steadily increased from 115 kV to 1000 kV for AC transmission lines; ±400 to ±800 kV DC lines have been either built or under construction worldwide [7]. However, in the U.S., constructing or upgrading a transmission line today is more complicated, compared to decades ago. Some factors responsible for this are listed below.

1. Social concerns about the impact of transmission lines.

Much more attention is paid to constructing and upgrading transmission lines today [9]. Electric and magnetic fields (EMF) and impacts of transmission lines on daily life have provoked intense criticism [10].

2. Laws and standards issued by governments and organizations.

In many states, the maximum values of transmission line electric and magnetic fields are regulated [11]. Organizations in power industry, such as Institute of Electrical and Electronics Engineers (IEEE), and Electric Power Research Institute (EPRI), also published standards to define acceptable transmission electric and magnetic fields criteria. The difficulty of constructing or upgrading higher voltage level transmission lines with limited right of way (ROW) increases because of those criteria.

3. Cost of the transmission line corridor.

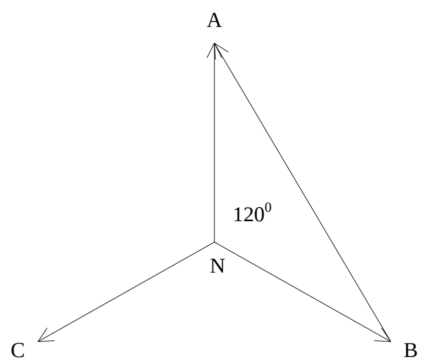
The cost of obtaining the transmission line corridor is expensive in those metropolitan areas and regions. Some residential communities have been built around existing transmission lines, and it is difficult to extend the right of way [9].

Line compaction, higher phase order systems, and high temperature low sag (HTLS) conductors, can be used to increase the power transfer capability of transmission lines with limited right of way [12]. The high phase order (HPO) transmission line technique was selected as the research topic of this thesis, due to the promise it holds for relieving the congestion. In this chapter, previous research and relevant technologies of high phase order transmission lines will be presented.

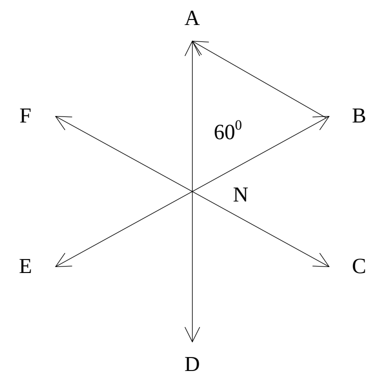
1.2 High phase order technology and research reviews

1.2.1 High phase order transmission introduction and history

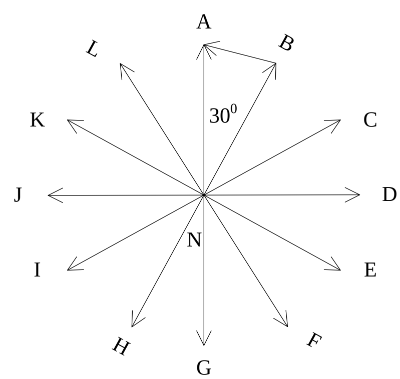
The idea of high phase order transmission was first introduced in 1973, by H. C. Barnes and L. O. Barthold [13]. The purpose of high phase order system was to convert the original three-phase power into six, nine, and twelve phase power. For the same phase-to-ground voltage, high phase order systems have lower phase-to-phase voltages, compared to a three-phase system. The phasors of three-phase and high phase order systems are shown in Fig. 1.1.



Three-phase



Six-phase



Twelve-phase

Fig. 1.1 Three-phase and high phase order phasors.

As shown in Fig. 1.1, the electrical angles between phases decrease as the phase order increases. Phase-to-phase voltage and phase-to-ground voltage of three-phase and high phase order systems can be expressed as follows,

$$V_{\lg 3\varphi} = V_{\lg 6\varphi} = V_{\lg 12\varphi} \tag{1.1}$$

$$V_{ll3\varphi} = \sqrt{3} V_{ll6\varphi} = 3 V_{ll12\varphi} \tag{1.2}$$

$$V_{ll6\varphi} = V_{\lg 6\varphi} \tag{1.3}$$

$$\sqrt{3}V_{ll12\varphi} = V_{\lg 12\varphi} \tag{1.4}$$

where

$V_{\lg 3\varphi}$, $V_{\lg 6\varphi}$, and $V_{\lg 12\varphi}$ are the phase-to-ground voltage of three-phase system, six-phase, and twelve-phase order respectively,

$V_{ll3\varphi}$, $V_{ll6\varphi}$, and $V_{ll12\varphi}$ are the phase-to-phase voltage of three-phase system, six-phase, and twelve-phase order respectively.

The power delivered by a three-phase transmission line and higher phase order transmission lines can be expressed as,

$$P_{3\varphi} = 3V_{\lg 3\varphi} I_{phase} \tag{1.5}$$

$$P_{6\varphi} = 6V_{\lg 6\varphi} I_{phase} \tag{1.6}$$

$$P_{12\varphi} = 12V_{\lg 12\varphi} I_{phase} \,. \tag{1.7}$$

It is assumed that phase-to-phase voltages and total currents in three-phase and high phase order transmission lines are equal. The power transfer capability of three-phase, six-phase, and twelve-phase order transmission lines can be expressed as,

$$P_{12\varphi} = \sqrt{3}P_{6\varphi} = 3P_{3\varphi} \,. \tag{1.8}$$

The equations above also indicate that if the same amount of power is to be delivered by high phase order transmission lines, phase-to-phase voltages in the high phase order system are lower, compared to the three-phase transmission line.

It suggests that less separation space between phases and smaller right of way are required in high phase order transmission lines [14].

In the 1970s, many researchers investigated high phase order transmission line design, analysis, and protection [14]. Symmetrical component theory was used to analyze high phase order fault in 1977 [15]. High phase order transmission line steady operation, overvoltage, and insulation issues were studied and discussed in J. R. Stewart's research [16]-[17]. The feasibility of upgrading a 138 kV double circuit three-phase transmission line to a six-phase transmission line was analyzed [18]. However, the idea of high phase order transmission lines was neglected at that time. The research on high phase order transmission lines was halted at the preliminary stage due to insufficient funding and support from utilities [14].

The milestone event of high phase order development was the testing of a six-phase line constructed in a testing facility in New York by the U.S. Department of Energy (DOE), and the New York State Energy Research and Development Authority (NYSERDA) in 1982. The final report of the test six-phase transmission line showed that "a six-phase transmission line can provide the same power transfer capability as three-phase with significantly less right of way for the same electric field and audible noise criteria, smaller transmission structures, and reduced overall cost" [19]. Due to the success of the six-phase line testing, the research of high phase order transmission lines made great progress. A twelve-phase transmission line study was conducted by Power Technologies International (PTI) in 1983 and an 115kV three-phase double circuit between

Goudey and Oakdale, New York, was reconfigured into a 93 kV six-phase single circuit line for demonstration purpose [20]. Based on the high phase order test lines and the six-phase demonstration project, research on high phase order transmission line power transfer capability, electric field, magnetic field, corona, fault analysis, reliability, economy, and stability aspects were conducted and published [21]-[27].

1.2.2 High phase order and three-phase conversion

As described above, higher phase order transmission lines are used to convert three-phase power to higher phase order power for delivery. It does not require high phase order generators to provide high phase power. It suggests that the high phase order transmission lines must be interconnected with the existing three-phase system. The interconnection between the high phase order transmission line and conventional three-phase system is shown in Fig. 1.2.

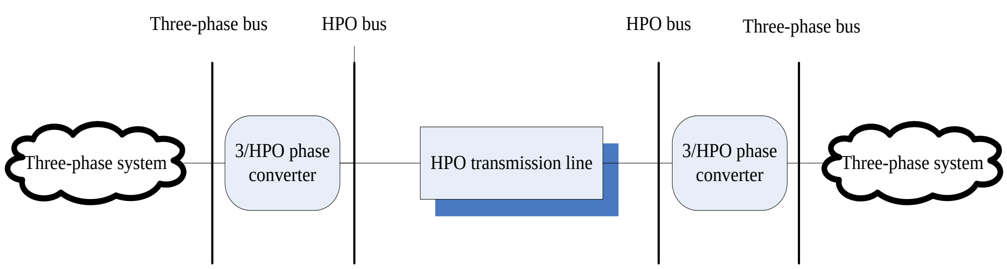


Fig. 1.2 Three-phase system and high phase order transmission line connection diagram.

The function of three/HPO phase converter block in Fig. 1.2 is to achieve correct phase-shifting between the three-phase and the high phase order system. Present techniques for phase-shifting from three-phase to higher phase can be classified into two categories [28]-[31]: (1) Transformer; (2) Power electronic device.

(1). Transformer based phase-shifting

Phase-shifting transformer techniques are based on electromagnetic coupling between transformer windings. Phase-shifting from three-phase to *N* phase order voltage, is achieved by different wiring connection of transformer windings. This technique has been studied and implemented for many years and different wiring connection methods were proposed and designed [28]. Some wiring methods for three-phase to *N*-phase transformers are shown from Figs. 1.3 to 1.6.

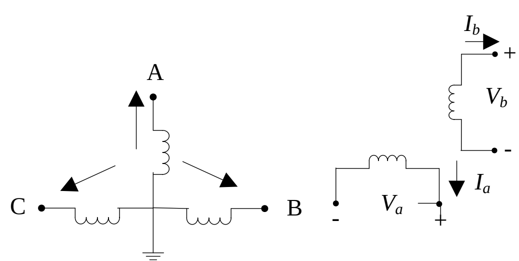


Fig. 1.3 Three-phase to split-phase transformer connection [28].

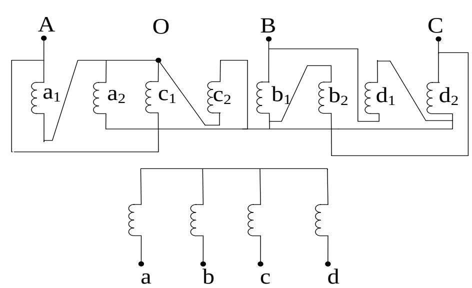


Fig. 1.4 Three-phase to four-phase transformer connection [28].

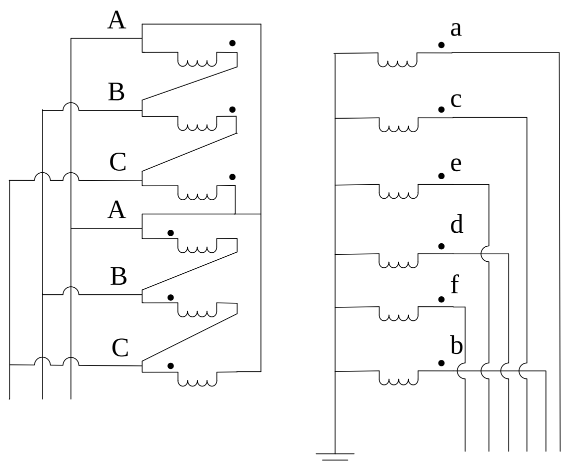


Fig. 1.5 Three-phase to six-phase transformer connection [29].

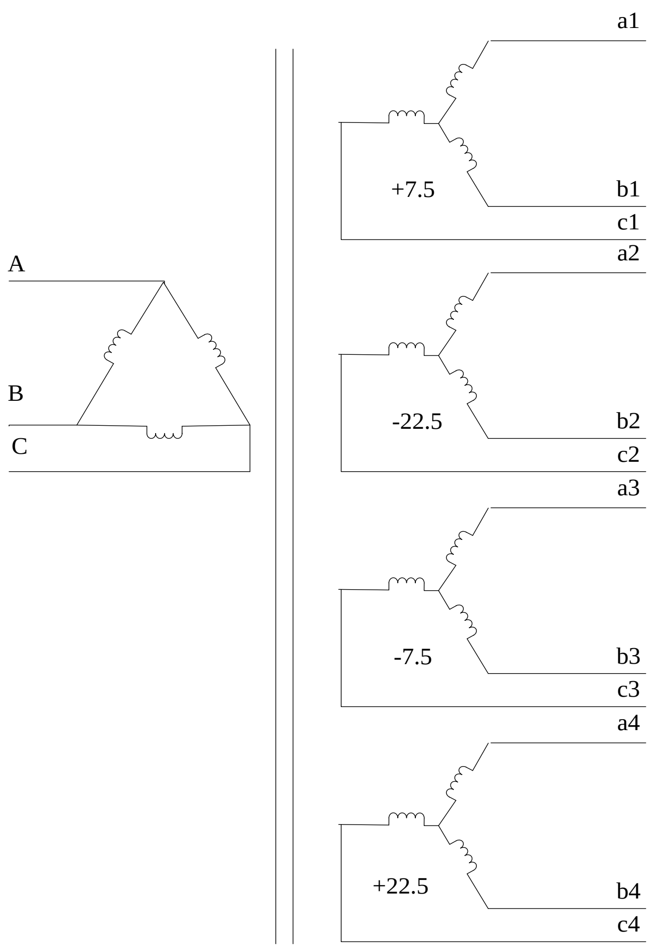


Fig. 1.6 Three-phase to twelve-phase transformer connection [30].

Many wiring connections required that transformer manufacturers abandon the conventional three-phase transformer structures and design new transformer structures for the three-phase to *N*-phase transformers. This requirement not only increased the cost of transformers, but also made the transformers difficult to be modeled in the existing commercial power area analysis and simulation software. Thus, many proposed transformer connections were not widely accepted by the industry.

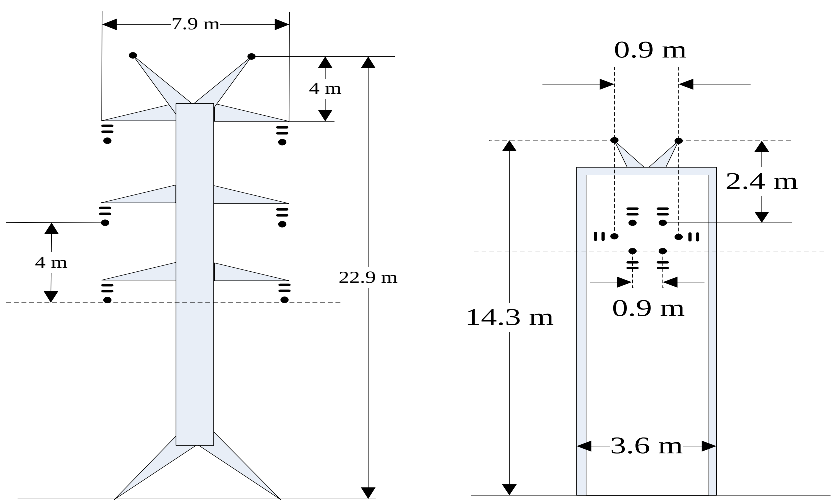
One economical and feasible method of the three-phase to six-phase transformer was proposed in J. R. Stewart's paper [29]. In this method, two conventional three-phase delta-Y transformers were connected in parallel to achieve a three-phase to six-phase transformer. The delta side of one transformer was inversely connected, as shown in Fig. 1.5. This connection method did not require any additional modification on the conventional three-phase transformer structure. Additionally, this transformers type can be modeled in power system analysis software, e.g., PSCAD/EMTP. This transformer connection will be employed in this thesis.

(2). Power electronic devices

The power electronic devices can be used to achieve phase-shifting for high phase order transmission line. AC-AC converter with IGBT, thyristor, and symmetrically phase shifted carriers has been designed and presented [31]. Although the AC-AC converter is not originally designed for high phase order application, it does have the ability to achieve the phase-shifting for three-phase and high phase order voltage conversion. Compared to the transformer based phase shift techniques, power electronic devices are more expensive and complicated.

1.2.3 High phase order tower configuration

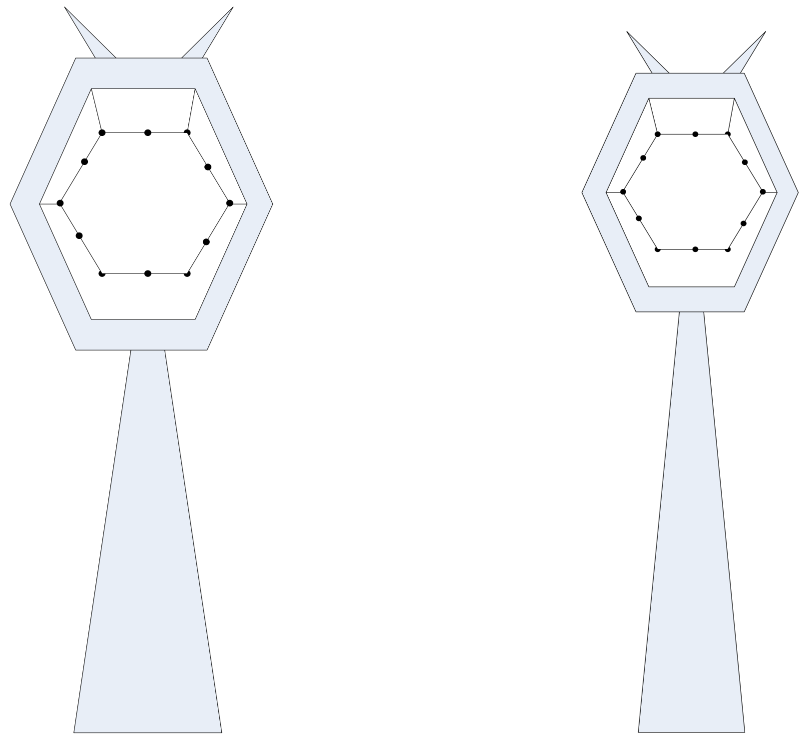
The benefits of high phase order systems arise from the smaller phase angles between phases [29]. As phase-to-phase voltage decreases, high phase order transmission lines generate lower conductor surface gradients and noise levels. This results in smaller space between phases. Some compact tower configurations were designed for high phase order transmission lines. Additionally, some three-phase double circuit line towers can also be employed in six-phase order transmission lines [29]. Some typical high phase order tower configurations, can be found in references [17] and [27], and are shown in Figs. 1.7, 1.8. Some important dimension date is listed in Table 1.1.



Conventional three-phase double circuit tower

Compact six-phase tower

Fig. 1.7 80 kV phase-to-ground tower configurations [17].



199 kV twelve-phase tower 133 kV twelve-phase tower

Fig. 1.8 Twelve-phase compact tower configuration [27].

TABLE 1.1
TWELVE-PHASE COMPACT TOWER DATA [27]

Tower case	Phase-to-ground Voltage (kV)	Phase-to-phase distance (m)	Minimum ground clearance (m)
199 kV twelve-phase tower	133	1.5	11.4
133 kV twelve-phase tower	199	2.3	11.4

1.3 Objective and proposed study

1.3.1 Objective

Research on high phase transmission has been conducted for many years. Several projects and simulations demonstrated the feasibility of higher phase transmission lines [16]-[29]. It should be noted that most of the previous research focused on comparing a three-phase single circuit line with a six-phase transmission line. The research on electric field, magnetic field, and fault analysis, was based on the assumption that the same amount of power was delivered by a three-phase single circuit line and a six-phase transmission line [29]. The impacts of different tower configurations and conductor numbers have not been investigated.

Six-phase transmission line is an optimum between the proportional increase in loading, and the proportional increase in surge impedance, which is obtained by increasing the number of phases with the increase in power transfer capability [2]. Thus, six-phase transmission line was selected in high phase order transmission line study. In this thesis, the main objective is to study the advantages of six-phase transmission lines, and to compare with the conventional three-phase double circuit line. The results will be helpful for identifying the better solution of transmission line upgrades and construction. The research includes line parameters, power transfer capability, electric field, magnetic field, right of way calculation, and fault analysis. To clarify the doubt about six-phase protection in reference [32], six-phase fault analysis and protection design, have also be studied in this thesis.

1.3.2 Cases studied and methodologies

To consider the impact of tower configurations, four cases were designed for three-phase double circuit line and six-phase transmission line comparison.

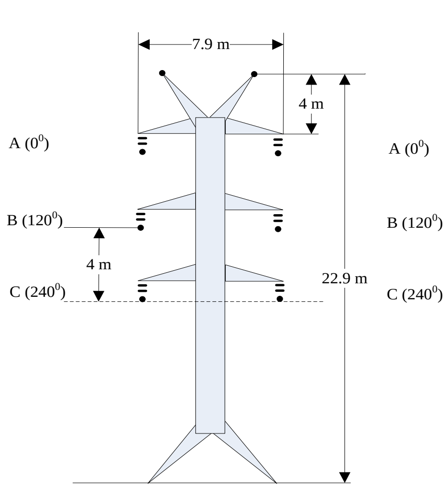
(1). 138 kV (80 kV phase-to-ground voltage level) three-phase double circuit transmission line with the conventional tower configuration.

(2). 80 kV six-phase transmission line with the conventional tower configuration.

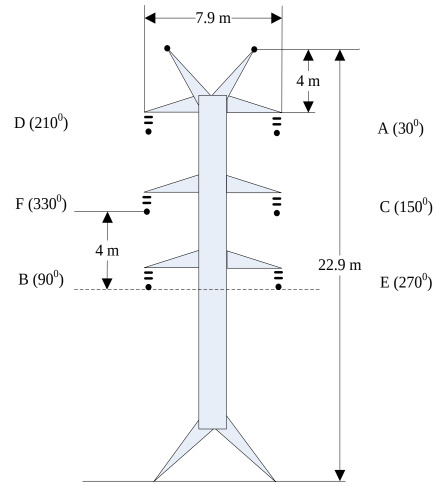
(3). 80 kV six-phase transmission line with compact tower configuration.

(4). 138 kV six-phase transmission line with the conventional tower configuration.

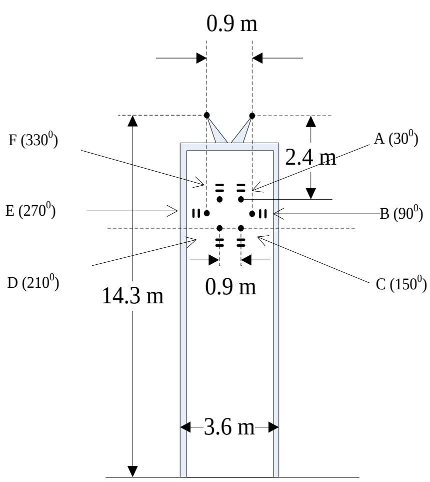
A 138 kV three-phase double circuit tower and an 80 kV six-phase compact tower configuration can be found in reference [17]. The tower configuration and phase arrangements of the four cases above are shown in Fig. 1.9.



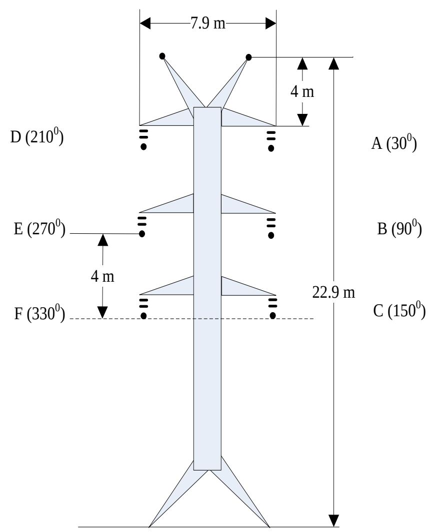
(1). 138 kV three-phase double circuit conventional tower line



(2). 80 kV six-phase conventional tower transmission line



(3). 80 kV six-phase compact tower transmission line



(4). 138 kV six-phase upgrading tower transmission line

Fig. 1.9 Three-phase and six-phase tower configuration and phase arrangements.

Based on the cases above, the following calculations and simulations will be conducted and the results will be calculated by a program developed using MATLAB.

(1). Power transfer capability calculations and comparisons.

In this section, it is assumed that the transmission line length is equal. The transmission line parameters of the four cases will be calculated. Based on line parameters results, the surge impedance and surge impedance loading (SIL) of the four cases will be calculated.

(2). Electric and magnetic fields calculations and comparisons.

In this section, electric and magnetic fields distributions at ground level of the four cases will be calculated.

(3). Right of way calculations and comparisons.

Based on electric and magnetic fields calculation results, right of way of the four cases will be calculated. Conductor sag and wind force will be included in the calculations.

(4). Fault current analysis.

In this section, three-phase double circuit line and six-phase transmission line faults will be calculated and analyzed. Powerworld® and PSCAD® will be used in this section.

(5). Six-phase protection system design.

In this section, a six-phase transmission line protection system will be designed based on the recommendation in reference [33]. Based on reference [34], an external tripping logic will be designed to coordinate the fault trip operation in two protection groups.

CHAPTER 2

TRANSMISSION LINE PARAMETERS

The power transfer capability of transmission lines can be evaluated by surge impedance loading, steady-state stability limit, thermal limit, and maximum power flow [35]. The thermal limit depends on environmental factors, such as solid condition, wind speed, and temperature. Additionally, surge impedance loading, steady-state stability limit, and maximum power flow are all dependent on surge impedance, and system operation status. Only surge impedance loading is used to evaluate and compare the power transfer capability of three-phase double circuit and six-phase transmission line in this thesis. To calculate surge impedance loading, the following line parameters will be calculated in this chapter: (1) Self and mutual impedance; (2) Capacitance; (3) Surge impedance. The transmission lines will be assumed to be completely transposed.

2.1 Transmission lines impedance

Transmission line impedance depends on many factors, such as, transmission line conductors, solid condition, temperature, and frequency ("skin effect") [35]. It is assumed that all these factors are equal in the calculations. For example, all the four cases analyzed in this thesis will be considered to be constructed on average damp earth and operated at 60 Hz frequency. The impedance calculation process for a three-phase single circuit line with horizontal configuration will be introduced in this section, and the same process will be extended to calculate the four cases proposed in Chapter 1.

The configuration of three-phase single circuit horizontal transmission line is shown in Fig 2.1.

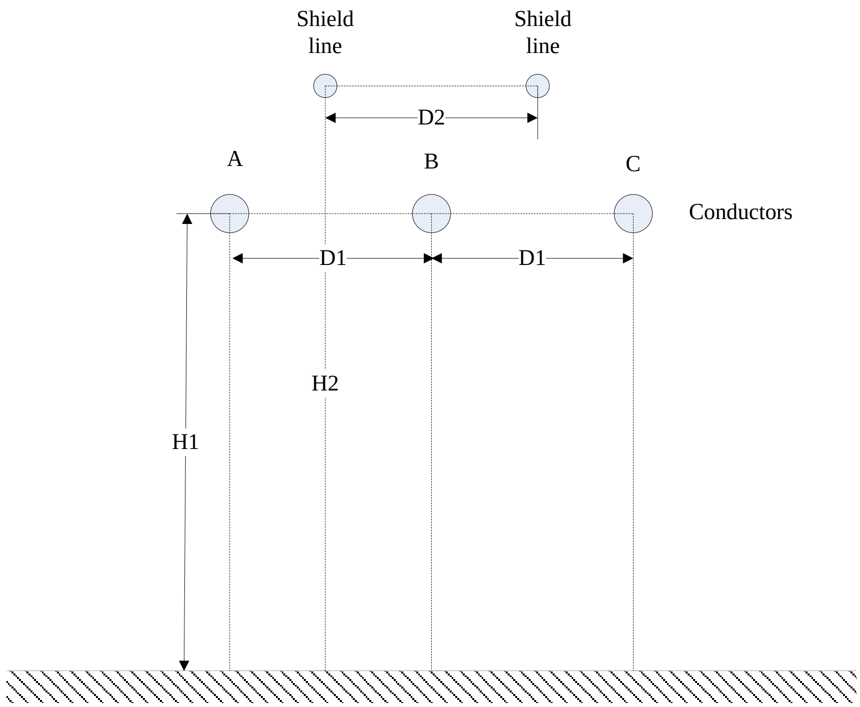


Fig. 2.1 Three-phase single circuit horizontal transmission line configuration.

To consider the effect of return current caused by earth, the earth return effects can be replaced by sets of earth return (image) conductors located under the transmission line conductors [36]-[38], as shown in Fig. 2.2.

As shown in Fig. 2.2, the conductors and earth return conductors have been renumbered. The currents of the earth return conductors are the negative values of their overhead currents. The distances of the earth return conductors from their overhead conductors are calculated by,

$$H_n = 658.5\sqrt{\rho / f} \tag{2.1}$$

where ρ is the earth resistivity and f is the frequency in Hz.

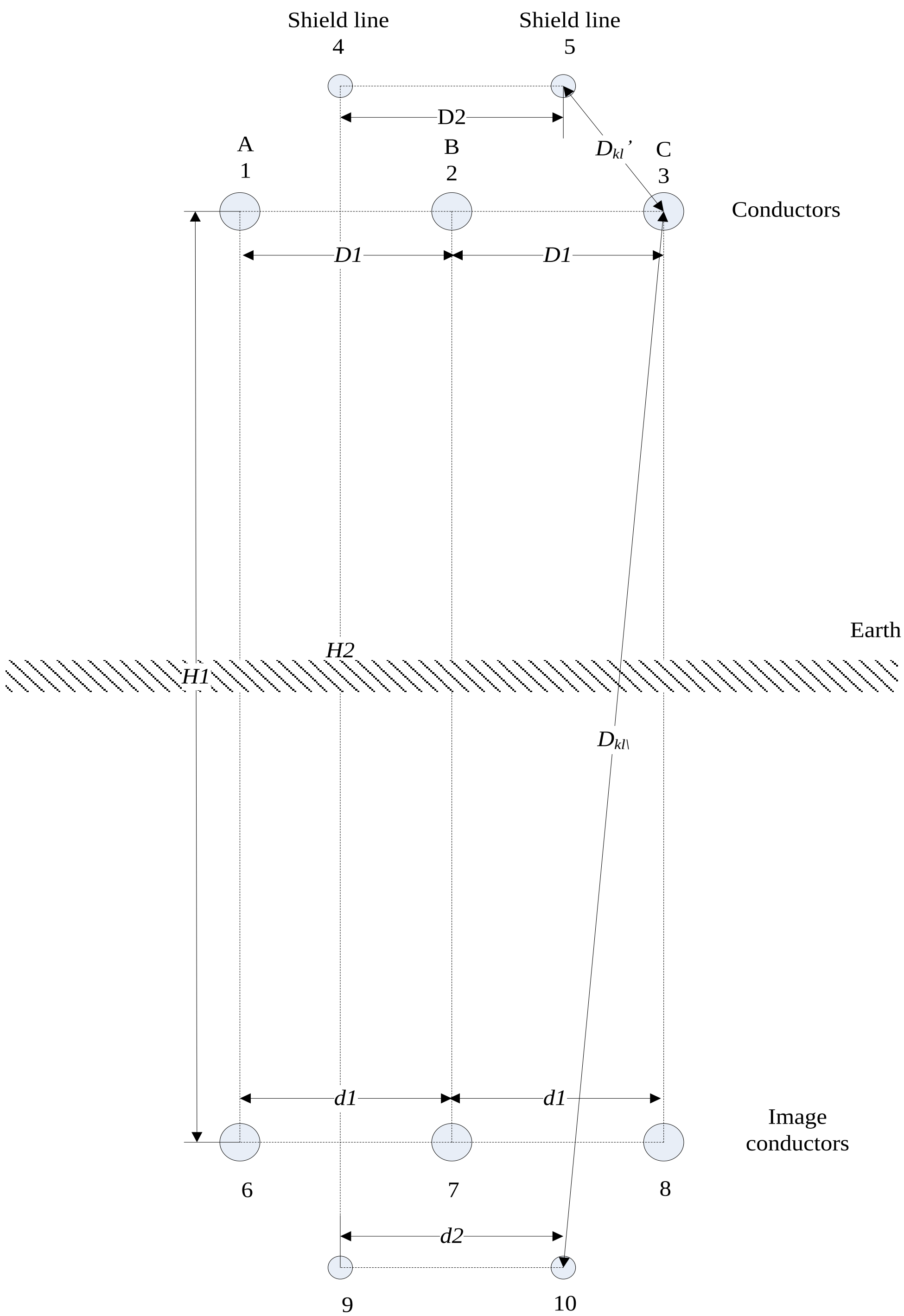


Fig. 2.2 Three-phase single circuit transmission line with earth return conductor.

Based on the Fig. 2.2, the conductors flux linkages can be calculated by,

$$\Phi_{k,l} = \sum_{l=1}^{m} I_{con} \frac{\mu_0}{2\pi} \ln(\frac{D_{kl'}}{D_{kl}}) \quad (2.2)$$

where

I_{con} is the current going through each conductor

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$D_{kl'}$ and D_{kl} are the distances between conductors

m is the number of overhead and image conductors

k, l =1,2,3,….10.

The reactance can be calculated by,

$$x_{k,l} = 2\pi f \frac{\Phi_{k,l}}{I_k} \quad (2.3)$$

The resistance can be calculated by,

$$r_{k,l} = r_{ground} \quad (2.4)$$

$$r_{k,k} = r_{ground} + r_{con} \quad (2.5)$$

Where

r_{ground} is the mutual resistance due to earth return conductors

r_{con} is the resistance of conductors, which depends on conductor types.

The impedance of the three-phase single circuit line, considering earth return conductors, can be presented as a matrix,

$$
\boldsymbol{Z}_{matrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & \dots & Z_{1(3+n)} \\ Z_{21} & Z_{22} & Z_{23} & Z_{\dots} & Z_{2(3+n)} \\ Z_{31} & Z_{32} & Z_{33} & \dots & Z_{3(3+n)} \\ \dots & \dots & \dots & \dots & \dots \\ Z_{(3+n)1} & Z_{(3+n)2} & Z_{(3+n)3} & \dots & Z_{(3+n)(3+n)} \end{bmatrix}. \tag{2.6}
$$

Equation (2.6) can be simplified by Gauss elimination as below,

$$
\boldsymbol{Z'}_{matrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}. \tag{2.7}
$$

Since the transmission line is assumed to be completely transposed, then

$$
Z_{11} = Z_{22} = Z_{33}
$$

All the non-diagonal elements are equal. More details of impedance calculation procedure can be found in reference [35].

The impedance calculation process can be extended to the three-phase double circuit line and six-phase transmission line. The calculation results are completely transposed 6×6 matrices, and the data of each transmission line are listed in Table 2.1.

The results show that transmission line impedance is determined by spacing between the conductors and conductor positions. The impedance of 80 kV six-phase compact tower transmission line is lower than other cases. This is due to low spacing in compact transmission line tower. However, the impact of transmission line tower size is small. As shown in Table 2.1, mutual impedance of 80 kV six-phase compact tower transmission line only increases by 10%, while the tower size decreases by 38%.

TABLE 2.1
IMPEDANCE OF THREE-PHASE AND SIX-PHASE TRANSMISSION LINES

Case name	Self impedance (Ω/km)	Mutual impedance (Ω/km)
138 kV three-phase double circuit tower conventional line	0.1 + j 0.8	0.1 + j 0.4
80 kV six-phase conventional tower line	0.1 + j 0.8	0.1 + j 0.4
80 kV six-phase compact tower line	0.1 + j 0.8	0.1 + j 0.5
138 kV six-phase conventional tower line	0.1 + j 0.8i	0.1 + j 0.4

2.2 Transmission lines capacitance

Similar as Section 2.1, the transmission line capacitance calculation can be derived by a three-phase single circuit line with a horizontal configuration. The tower configuration is shown in Fig. 2.1. When the transmission line is energized, negative charges are induced on the ground. To replace the earth return effects, image conductors were also introduced as Section 2.1. The depth of image conductor is equal to the height of the overhead conductors: $h_n=H_N$.

The voltage differences between conductors and ground can be calculated by

$$V_{k,l} = \frac{1}{2\pi\varepsilon_0}\sum_{l=1}^{m} q_{con} \ln(\frac{D_{kl'}}{D_{kl}}) \tag{2.8}$$

where

$\varepsilon_0 = 8.854\times10^{-12}$ F/m

q_{con} is conductor charges

$D_{kl'}$ and D_{kl} are the distances between conductors

m is the number of overhead and image conductors

k, l=1,2,3,....., m.

Since the voltage difference can be also presented in matrix format as,

$$\boldsymbol{V} = \boldsymbol{Pq} \quad (2.9)$$

The potential coefficients $\boldsymbol{P}$ can be calculated as,

$$P_{k,l} = \frac{1}{2\pi\varepsilon_0}\sum_{l=1}^{m}\ln\left(\frac{D_{kl'}}{D_{kl}}\right) \quad (2.10)$$

where

m is the number of overhead and image conductors.

The results of potential coefficients can be expressed in (3+N) × (3+N) matrix as below,

$$\boldsymbol{P} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1(3+n)} \\ P_{21} & P_{22} & P_{23} & Z_{\cdots} & P_{2(3+n)} \\ P_{31} & P_{32} & P_{33} & \cdots & P_{3(3+n)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{(3+n)1} & P_{(3+n)2} & P_{(3+n)3} & \cdots & P_{(3+n)(3+n)} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P_A} & \boldsymbol{P_B} \\ \boldsymbol{P_C} & \boldsymbol{P_D} \end{bmatrix} \quad (2.11)$$

where

$$\boldsymbol{P_A} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix}, \quad \boldsymbol{P_B} = \begin{bmatrix} P_{1(3+1)} & \cdots & P_{1(3+n)} \\ P_{2(3+1)} & \cdots & P_{2(3+n)} \\ P_{3(3+1)} & \cdots & P_{3(3+n)} \end{bmatrix},$$

$$\boldsymbol{P_C} = \begin{bmatrix} P_{(3+1)1} & P_{(3+1)2} & P_{(3+1)3} \\ \cdots & \cdots & \cdots \\ P_{(3+n)1} & P_{(3+n)2} & P_{(3+n)3} \end{bmatrix} \text{ and } \boldsymbol{P_C} = \begin{bmatrix} P_{(3+1)1} & P_{(3+1)2} & P_{(3+1)3} \\ \cdots & \cdots & \cdots \\ P_{(3+n)1} & P_{(3+n)2} & P_{(3+n)3} \end{bmatrix}.$$

The capacitance of the transmission line can be calculated in matrix format as,

$$\boldsymbol{C_P} = (\boldsymbol{P_A} - \boldsymbol{P_B}\boldsymbol{P_D}^{-1}\boldsymbol{P_C})^{-1} . \tag{2.12}$$

Since the transmission line is assumed to be completely transposed, $\boldsymbol{C_p}$ is a 3×3 symmetrical matrix. More details of impedance calculation procedure can be found in reference [35].

The capacitance calculation procedures can be extended to the three-phase double circuit line and six-phase transmission line. The capacitances of each transmission line are listed in Table 2.2.

TABLE 2.2
CAPACITANCE OF THREE-PHASE AND SIX-PHASE TRANSMISSION LINES

Case name	Self capacitance (nF/km)	Mutual capacitance (nF/km)
138 kV three-phase double circuit conventional tower line	8.3	-1.2
80 kV six-phase conventional tower line	8.3	-1.2
80 kV six-phase compact tower line	11.7	-2.5
138 kV six-phase conventional tower line	8.3	-1.2

The results show that the 80 kV six-phase compact tower transmission line self capacitance, is higher than other cases, while the mutual capacitance is lower. This is due to compact transmission line tower. The impact of tower size on transmission line capacitance is considerable. As shown in Table 2.2, in 80 kV six-phase compact tower transmission line, the self capacitance is about 41% higher than the capacitance in other cases, and the mutual capacitance is about 200% of the other cases. Shunt capacitance of the six-phase compact transmission line is significantly higher. High value of shunt capacitance in a transmission line may result in a high voltage at the receiving end of the transmission line, under a light load condition. Additionally, high charge currents may also reduce the sensitivity of transmission line protection systems.

2.3 Surge impedance and surge impedance loading

The surge impedance and surge impedance loading are calculated based on the π model of a lossless line shown in Fig. 2.3.

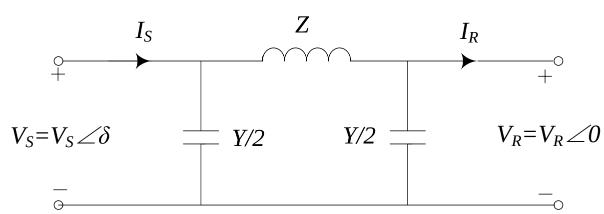


Fig. 2.3 Equivalent π circuit for a lossless line.

In the model, *Z* is series impedance per mile and *Y* is shunt admittance. The surge impedance can be calculated as:

$$Z_c = \sqrt{\frac{L}{C}} \tag{2.13}$$

Then, surge impedance loading can be calculated as:

$$SIL = \frac{kV_{rated}^2}{Z_c} \tag{2.14}$$

where

V_{rated} is phase-to-ground voltage

k is the number of conductors.

According to the results from Section 2.1 and 2.2, the surge impedance and surge impedance loading of four cases was calculated and listed in Table 2.3.

TABLE 2.3
SURGE IMPEDANCE AND SIL OF THREE-PHASE AND SIX-PHASE TRANSMISSION LINES

Case name	Surge impedance(Ω)	SIL (MW)
138 kV three-phase double circuit tower line	491.0	78.2
80 kV six-phase conventional tower line	491.0	78.2
80 kV six-phase compact tower line	413.1	93.0
138 kV six-phase conventional tower line	491.0	231.7

The results show the surge impedances declines and surge impedance loading increases in six-phase compact tower transmission line. The surge impedance of six-phase transmission line with compact tower is about 15% less than the transmission line conventional tower. As a consequence, surge impedance loading of six-phase compact tower transmission line is about 18% higher than the three-phase double circuit transmission line. Due to the increase of phase-to-ground voltage in the 138 kV six-phase conventional tower case, surge impedance loading of the transmission line is about 297% of the three-phase double circuit transmission line with the same tower configuration.

CHAPTER 3

ELECTRIC AND MAGNETIC FIELD CALCUALTIONS

Electric and magnetic field are significant in the overall design of transmission line. Electric and magnetic field strengths of transmission line directly determine many other criteria of transmission lines; such as corona, communication interference and audible noise. Electric and magnetic field distributions at ground level are compared and evaluated in this chapter. The performance of electric and magnetic field distributions at ground level were calculated and plotted by a program developed using MATLAB codes.

3.1 Electric field distribution at ground level

The transmission line electric field at ground is determined by superposition of electric field generated by all conductors. The calculation procedure is explained as below.

The electric field, generated by conductor k, at point x is shown in Fig. 3.1. To consider earth return effects, an image conductor is introduced and the charges of the image conductor are the negative values of its overhead charges.

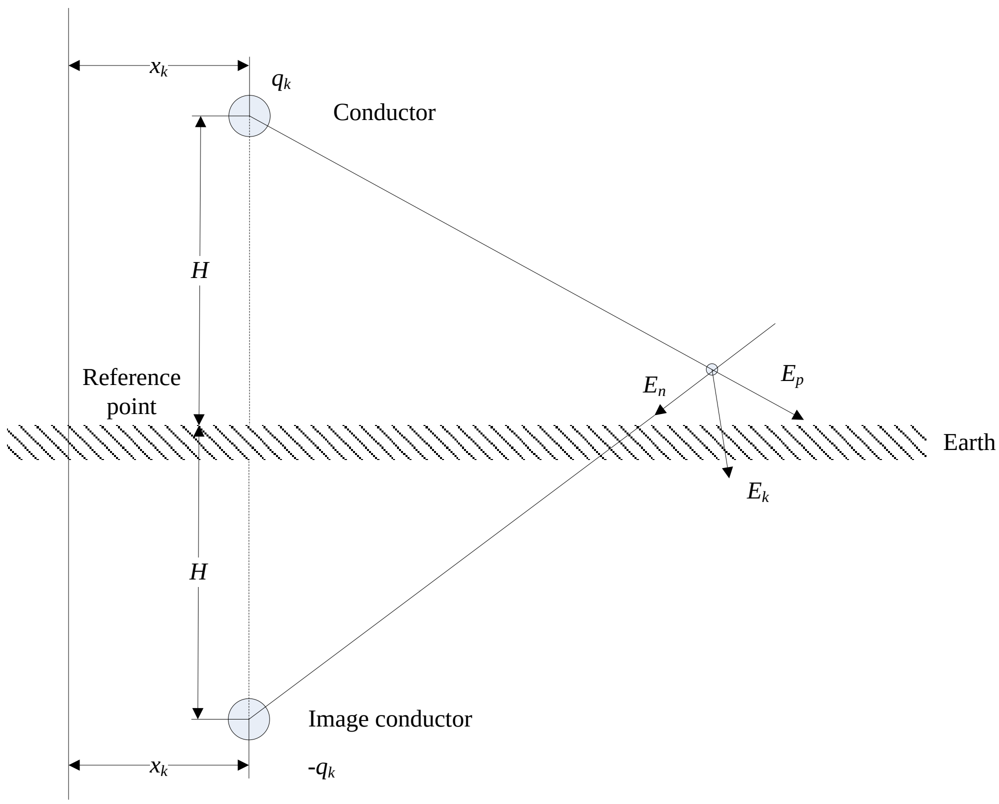


Fig. 3.1 Electric field strength due to an overhead conductor and its image conductor.

As shown in Fig. 3.1, the electric field at point x due to charges on conductor k and its image conductors can be calculated by,

$$E_{kp}(x) = \left(\frac{q_k}{2\pi\varepsilon_0}\right)\frac{1}{\sqrt{(x_k - x_x)^2 + (y_k - y_x)^2}} \quad (3.1)$$

$$E_{kn}(x) = \left(\frac{q_k}{2\pi_{\varepsilon_0}}\right)\frac{1}{\sqrt{(x_k - x_x)^2 + (y_k + y_x)^2}} \quad (3.2)$$

Where

q_k is the charge on conductor k

$$\varepsilon_0 = \frac{10^{-9}}{36\pi} F/m$$.

The charges on conductors can be calculated in matrix format,

$$\boldsymbol{Q} = \boldsymbol{P}^{-1}\boldsymbol{V}_{ln} . \tag{3.3}$$

The elements of P are the potential coefficients which can be calculated by,

$$P_{k,l} = \frac{1}{2\pi\varepsilon_0} \sum_{m=a}^{lN} \ln\left(\frac{D_{kl'}}{D_{kl}}\right) \tag{3.4}$$

where

$D_{kl'}$ and D_{kl} are the distances between conductors.

Since the electric field is a vector, any electric field generated by one conductor and its image conductor can be expressed by real and imaginary parts,

$$\tilde{E}_{kp}(x) = \tilde{E}_{kpx}(x) + j\tilde{E}_{kpy}(x) \tag{3.5}$$

and

$$\tilde{E}_{kn}(x) = \tilde{E}_{knx}(x) + j\tilde{E}_{kny}(x) . \tag{3.6}$$

The electric field at the x point is the superposition of electric field generated by one conductor and its image conductor,

$$\tilde{E}_k(x) = \tilde{E}_{kpx}(x) + \tilde{E}_{knx}(x) + j(\tilde{E}_{kpy}(x) + \tilde{E}_{kny}(x)) . \tag{3.7}$$

The total electric field at the x point can be calculated by,

$$\tilde{E}_x(x) = \tilde{E}_{1px}(x) + \tilde{E}_{1nx}(x) + \ldots + \tilde{E}_{(3+n)px}(x) + \tilde{E}_{(3+n)nx}(x) \tag{3.8}$$

$$\tilde{E}_y(x) = \tilde{E}_{1py}(x) + \tilde{E}_{1ny}(x) + \ldots + \tilde{E}_{(3+n)py}(x) + \tilde{E}_{(3+n)ny}(x) \tag{3.9}$$

and

$$\tilde{E}(x) = \tilde{E}_x(x) + j\tilde{E}_y(x) \quad (3.10)$$

The electric field distribution can be plotted based on the calculation of electric field at each point of ground level. More details about electric field calculation can be found in reference [39].

The electric field calculation procedure can be extended to the three-phase double circuit line and six-phase transmission lines proposed in Chapter 1. The electric field distributions of the proposed cases are plotted in Figs. 3.2-3.5.The summary of the calculation results are listed in the Table 3.1.

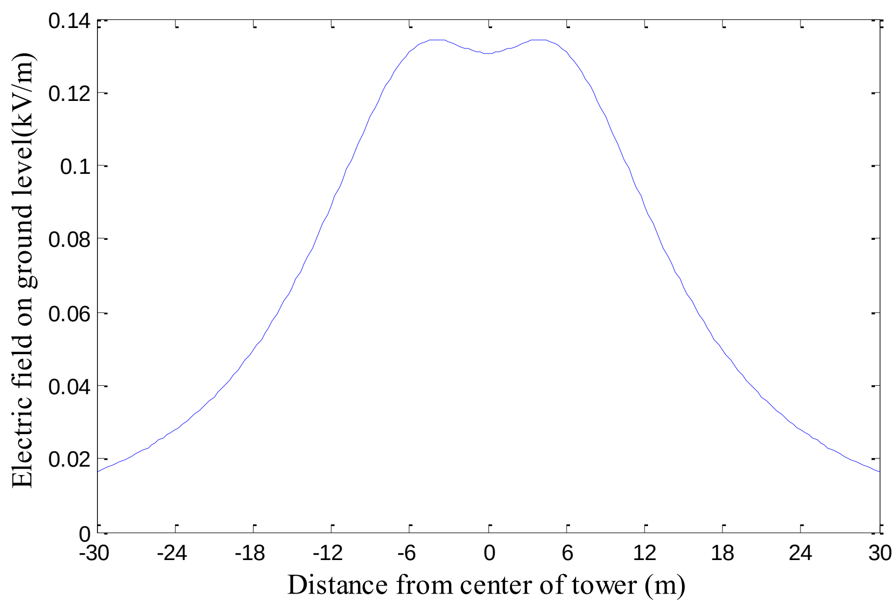


Fig. 3.2 138 kV three-phase double circuit tower transmission line electric field distribution at ground level.

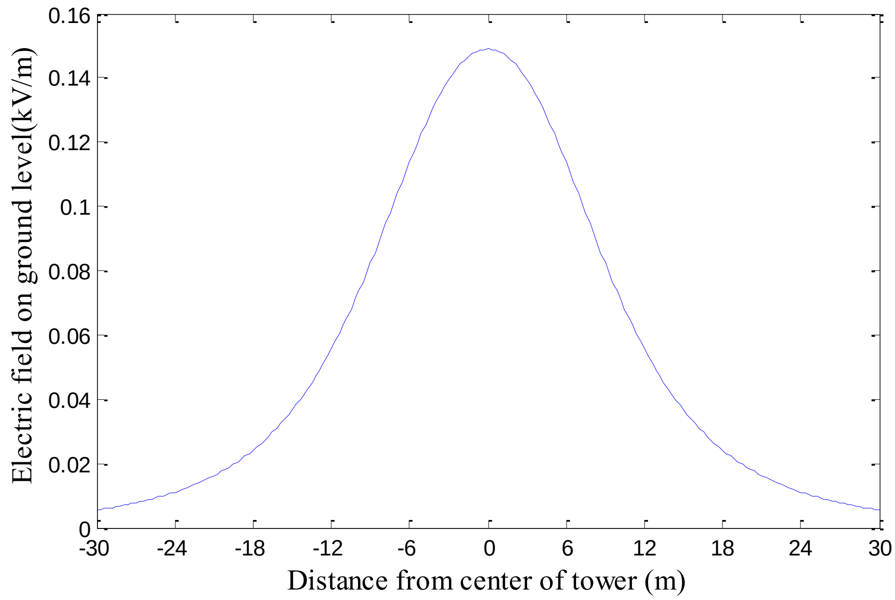


Fig. 3.3 80 kV six-phase conventional tower transmission line electric field distribution at ground level.

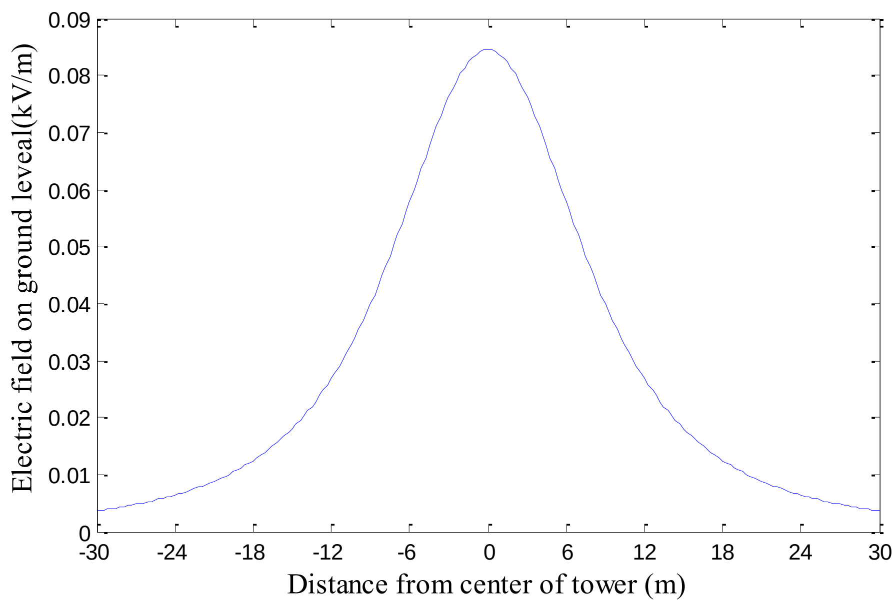


Fig. 3.4 80 kV six-phase compact tower transmission line electric field distribution at ground level.

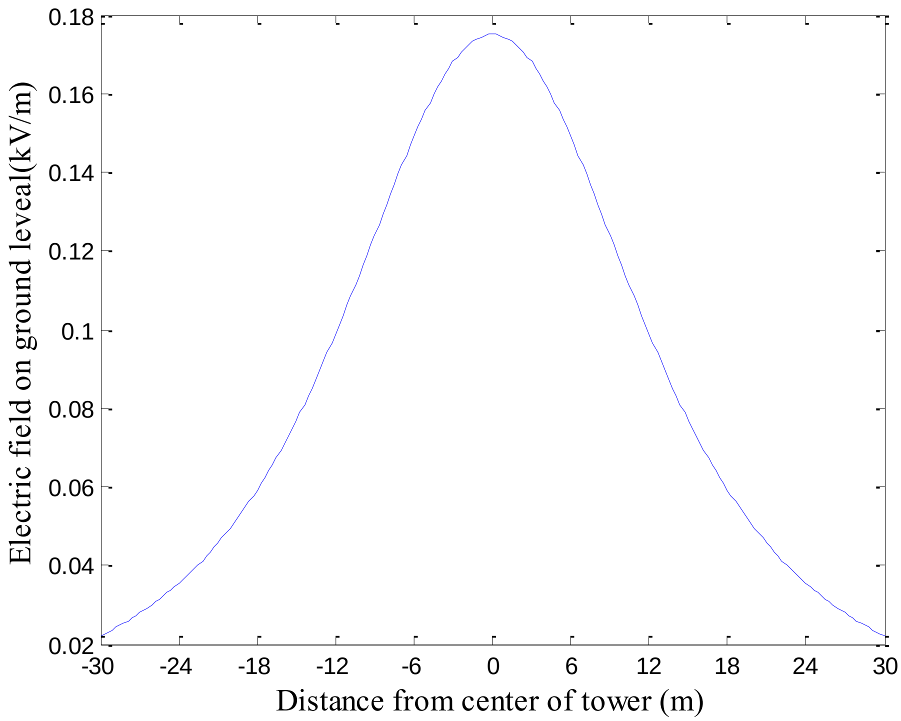


Fig. 3.5 138 kV six-phase compact tower transmission line electric field distribution at ground level.

TABLE 3.1
SUMMARY OF ELECTRIC FIELD CALCULATION AT GROUND LEVEL

Case name	Maximum electric field (kV/m)	Electric field at edge of ROW (kV/m)
138 kV three-phase double circuit conventional tower line	0.1	0.03
80 kV six-phase conventional tower line	0.2	0.01
80 kV six-phase compact tower line	0.1	0.01
138 kV six-phase conventional tower line	0.2	0.04

In Table 3.1, right of way was selected as 46 m (150 ft). As the results show, the maximum electric field under six-phase transmission line is higher than the values under three-phase double circuit line. With the same tower and the phase-to-ground voltage level, the maximum electric field under the six-phase transmission line is only about 10% higher than the value under three-phase double circuit line. Thus, the maximum electric field under the six-phase transmission line can be considered as acceptable. However, it should be noted that, as the distance from the center of tower increases, electric field under the six-phase transmission lines decline much faster than the electric field under three-phase double circuit transmission line. This result is due to the effective canceling out of electric field generated by six-phase transmission line conductors. This means that six-phase transmission line may require less right of way when the same amount of power is delivered. The details of the right of way will be evaluated and compared in the next chapter.

3.2 Magnetic field distribution at ground level

Concerns about magnetic field are mainly due to possible biological effects. The potential hazards to human health from transmission lines have been investigated for years [40]. Although there is no definite conclusion about the concern caused by magnetic field, many organizations and states have published some requirements and laws about magnetic field limitations [11], [41]. In this thesis, the magnetic field distribution at ground level are evaluated and compared. Magnetic field is generated by the currents through conductors. The calculation procedures of magnetic field are described below.

As shown in Fig. 3.6, the magnetic field strength at point *x*, generated by conductor *k*, can be calculated by,

$$H_k(x) = \frac{I_k}{2\pi d_{kx}} \tag{3.10}$$

where

d_k is the distance between conductor *k* and selected the point *x*

I_k is the current going through the conductor *k*.

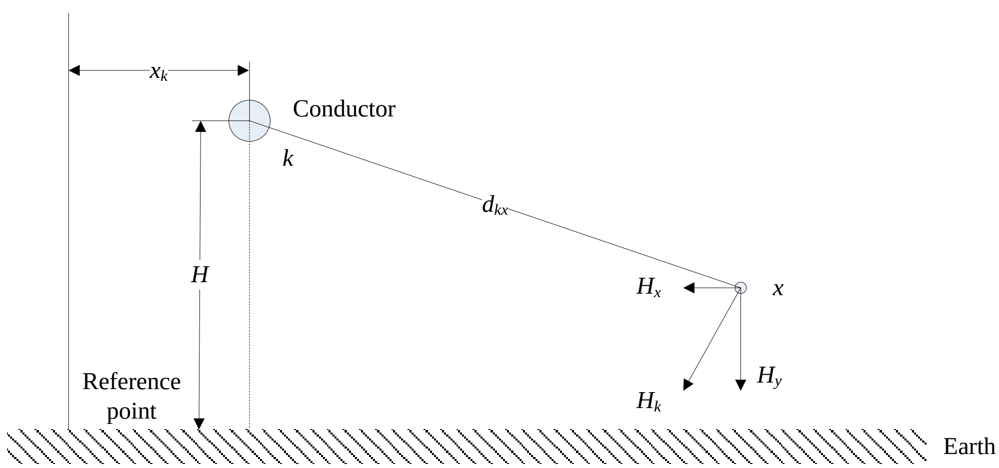


Fig. 3.6 Magnetic field strength due to an overhead conductor.

Magnetic field strength generated by conductor *k* is a vector, which can be expressed by real and imaginary parts,

$$H_k(x) = H_{kx}(x) + jH_{ky}(x) \tag{3.11}$$

The total magnetic field strength is the vector summation of the *x* and *y* magnetic field components generated by all conductors,

$$H(x) = \sum_{k=1}^{m} H_{kx}(x) + j\sum_{k=1}^{m} H_{ky}(x) \qquad (3.12)$$

where

m is the conductor number

k=1, 2…m.

Magnetic field density (B), which is a more common criterion to evaluate magnetic field, can be calculated by,

$$B(x) = \mu_0 H(x) \qquad (3.13)$$

where

$\mu_0 = 4\pi 10^{-7}\,\mathrm{H/m}$.

The magnetic field calculation procedure can be extended to the three-phase double circuit and six-phase transmission lines proposed in Chapter 1. The magnetic field distributions of the proposed scenarios are plotted in Figs. 3.7-3.10. The summary of the calculation results are listed in Table 3.2.

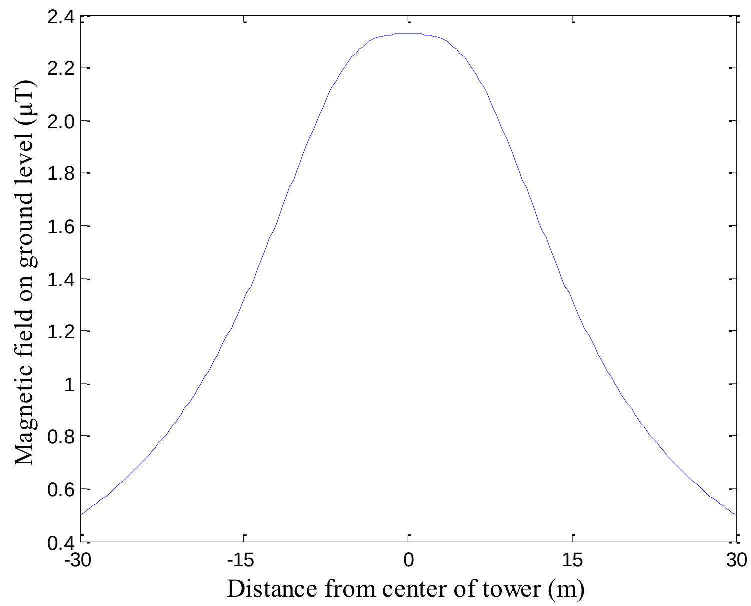


Fig. 3.7 138 kV three-phase double circuit tower transmission line magnetic field distribution at ground level.

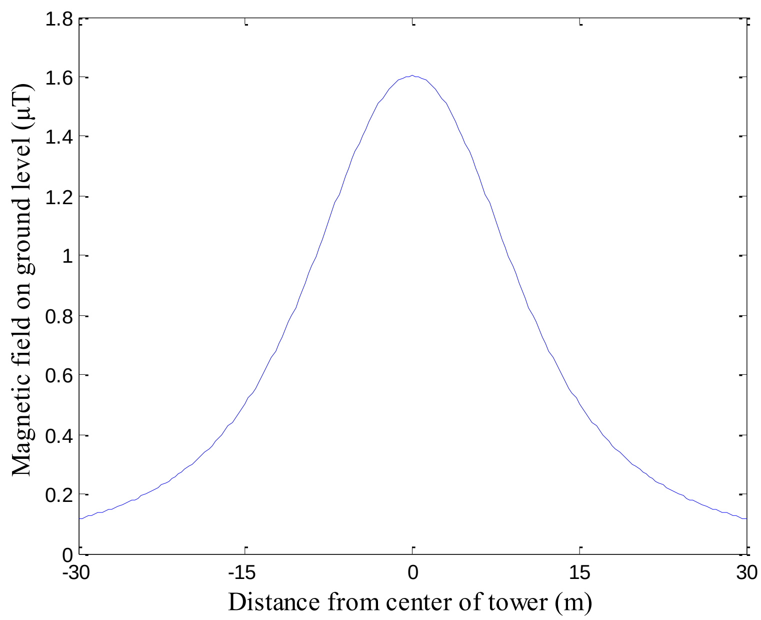


Fig. 3.8 80 kV six-phase conventional tower transmission line magnetic field distribution at ground level.

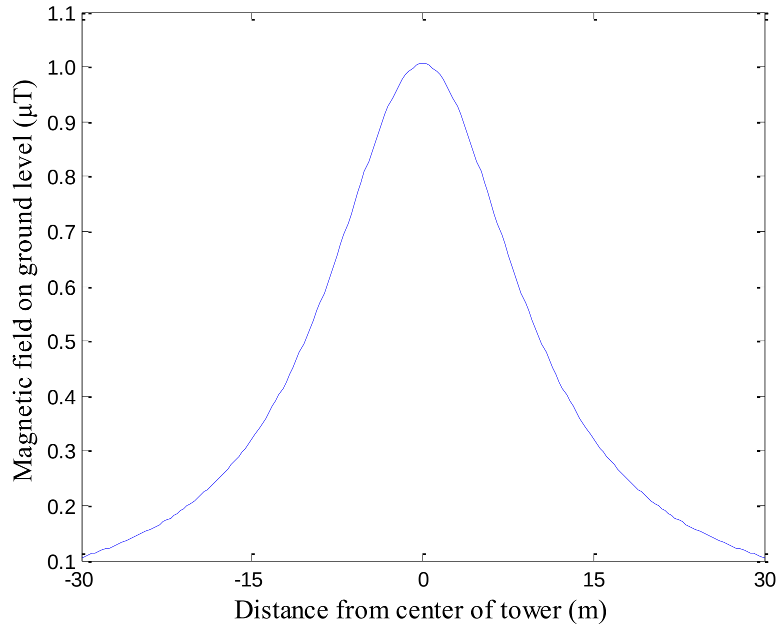


Fig. 3.9 80 kV six-phase compact tower transmission line magnetic field distribution at ground level.

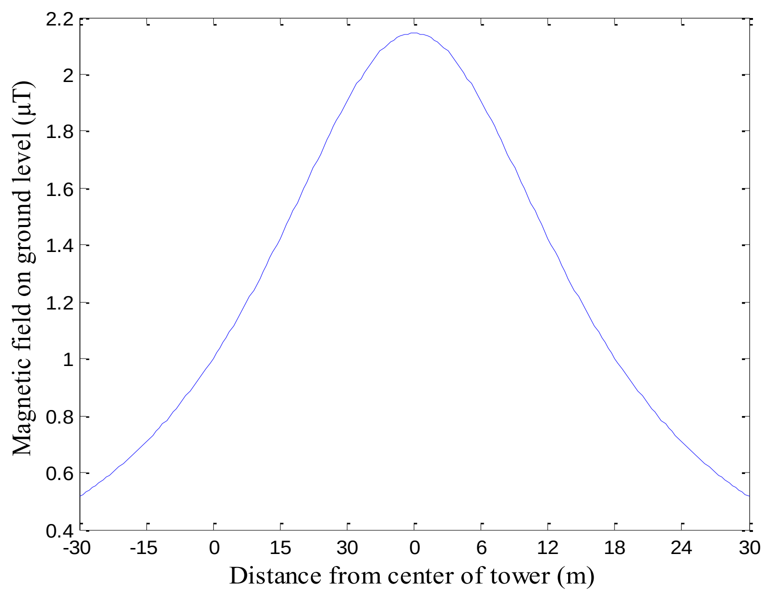


Fig. 3.10 138 kV six-phase compact tower transmission line magnetic field distribution at ground level.

TABLE 3.2
RESULTS SUMMARY OF MAGNETIC FIELD AT GROUND LEVEL

Case name	Maximum magnetic field (μT)	Magnetic field at edge of ROW (μT)
138 kV three-phase double circuit conventional tower line	2.3	0.8
80 kV six-phase conventional tower line	1.6	0.2
80 kV six-phase compact tower line	1.0	0.2
138 kV six-phase conventional tower line	2.1	0.8

In Table 3.2, 46 m (150 ft) was selected as right of way of the cases. As shown by the results, magnetic field under six-phase transmission lines is lower than the value under three-phase line. This is due to effective canceling out of magnetic field generated by six-phase transmission lines. Magnetic field decreases when six-phase transmission line tower is compacted. The result is that magnetic field under the 80 kV six-phase conventional tower transmission line is higher than the values under the line with compact tower. It should be noted that, phase arrangement in six-phase transmission line has significant influences on magnetic field. As indicated by the results, under same tower configuration and currents going through the conductors, magnetic field under 138 kV six-phase transmission line is much higher than the values under 80 kV six-phase transmission line.

CHAPTER 4

TRANSMISSION LINE RIGHT OF WAY CALCULATION

Right of way is significant in both transmission line design and construction cost. From the utilities viewpoint, the most important priority of right of way is preservation of its assets security with a satisfactory level [42]. This aspect of right of way will be not studied in this thesis. For the public concentration, appropriated right of way is to eliminate risk to human and property from transmission line electric and magnetic field. Potential hazards of electric and magnetic field to human health from living or working have been investigated for years. Although no definite conclusion has been drawn on the harms of electric and magnetic field to human beings, many states and organizations still published codes and standards to regulate transmission line electric and magnetic field at ground level[11],[43]-[44]. In this section, electric and magnetic field generated by the three-phase double circuit line within selected right of way, was calculated. The right of way for the six-phase lines to achieve the same field strengths was calculated and evaluated.

Transmission line right of way width calculation procedures are described as below:

As shown in Fig. 4.1, transmission line right of way can be calculated by,

$$ROW = 2(A + B + C) \tag{4.1}$$

where

A = Horizontal clearance to buildings

B = Conductor blowout due to angle (120 F °sag)

C= Distance from centerline of tower structure to outside conductor attachment point.

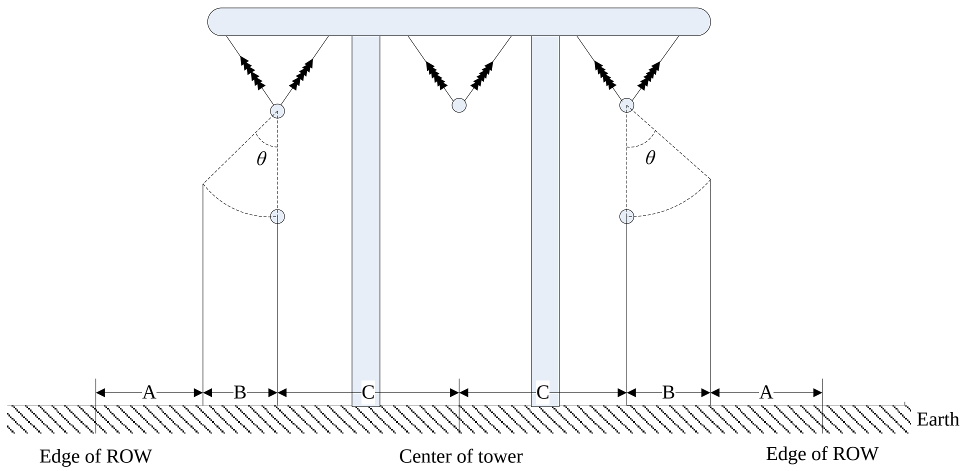


Fig. 4.1 Three-phase single circuit transmission line right of way.

In Fig. 4.1, horizontal clearance to buildings is determined by electric and magnetic field distributions at ground level, and also dependent on IEEE and state laws requirements. Conductor blowout is determined by wind force and conductor weight. In this thesis, the same transmission line environmental conditions and conductor types was assumed in the calculations.

Transmission line electric and magnetic field requirements from different organizations and states can be found in reference [11]; and summarized in Tables 4.1 and 4.2.

TABLE 4.1
ELECTRIC FIELD REFERENCE LEVELS SUMMARIZATION

Jurisdiction/organization	Maximum electric filed (kV/m)	Electric field at edge of ROW (kV/m)
IEEE	20	5
ICNIRP	8.3	4.2
ACGIH	25	-
NRPB	12	12
EU	-	4.2
New York	11.8	1.6
Montana	7	1

TABLE 4.2
MAGNETIC FIELD REFERENCE LEVELS SUMMARIZATION

Jurisdiction/organization	Maximum magnetic field (μT)	Magnetic field at edge of ROW (μT)
IEEE	2700	900
ICNIRP	400	800
ACGIH	1000	-
NRPB	1300	1300
EU	-	80
New York	-	20

The references levels above are defined for all transmission line voltage levels. Due to the relatively low voltage level of the proposed cases (138 kV), the ground level electric and magnetic field do not exceed the public safety requirements for right of way. For a better demonstration purpose, 46 m (150 ft) right of way was selected for the three-phase double circuit transmission line. The ground level electric and magnetic field at the edge of right of way, generated by 138 kV three-phase double circuit line, was calculated and set as the criteria in this thesis. The right of way requirements for the six-phase transmission lines were calculated to achieve the same ground level electric and magnetic field strength at the edge of right of way.

To calculate the right of way of the proposed cases, standard suspension insulators were selected as transmission line insulator type. The specifications of standard suspension insulators are listed in Table 4.3.

TABLE 4.3
STANDARD SUSPENSION INSULATOR SPECIFICATIONS

Type of insulation	Standard 5.75x10 insulators
Diameter	0.25 m
Connection distance	0.15m
Leakage distance	0.29 m
Insulation string configuration	6 Vertical strings per tower

According to reference [45], number of standard insulators units at moderate pollution level for a 138 kV vertical insulator string is 9. The total length of insulator string is calculated as follows,

$$D_{insulator} = 9 \times 146 = 1314.45\ mm \approx 1.3\ m\,.$$

Ice loading was not considered in this thesis. The insulator deviation (conductor blowout) is caused by wind force and conductor weight. According to reference [45], wind pressure is selected as 6 lb / sq ft (~ 31 mph) in the thesis.

$$P_{wind} = 6\ lb\ /\ sq\ ft$$

The area subjected to the wind is calculated as follows.

$$A_{wind} = D_{conductor} \times L_{span} = 0.03037 \times 304.8 = 9.3\ m^2$$

Wind force can be calculated by,

$$F_{wind} = P_{wind} \times A_{wind} = 29.29 \times 9.2568 = 271.1\ kg$$.

Conductor weight is $W_{cond} = 556.6\ kg$. The total force and its angle to the vertical line can be calculated as follows,

$$F_{total} = \sqrt{F_{wind}^{\ 2} + W_{cond}^{\ 2}} = 619.1\ kg$$

$$\theta = a\tan\left(\frac{F_{wind}}{W_{cond}}\right) = 26^o$$.

Single bundle and CARDINAL/ACSS are chosen as transmission line conductors. The transmission line span is chosen as 300 m. Sag of conductors is chosen at 120 ^oF: 0.94 m.

Based on the assumptions and results above, electric and magnetic field distributions at ground level of proposed cases, can be calculated by the method described in Chapter 3. The electric and magnetic field distributions are plotted in Fig. 4.2-4.9.

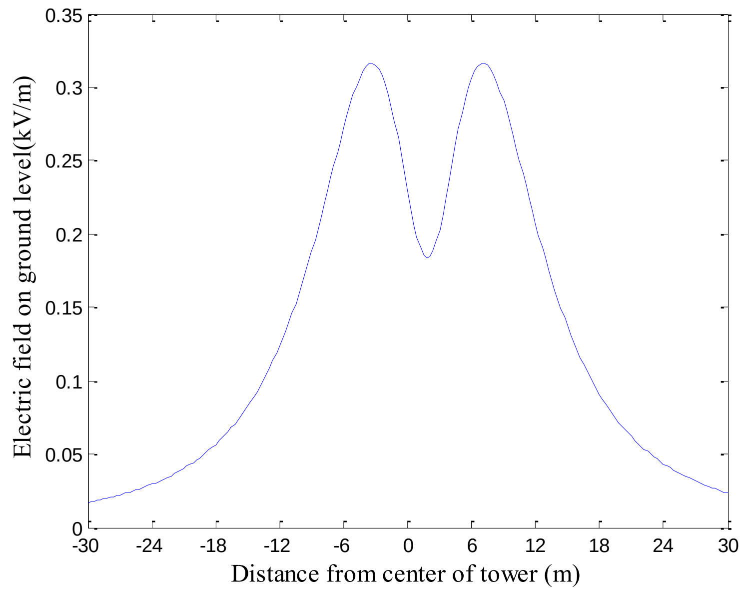


Fig. 4.2 138 kV three-phase double circuit tower transmission line electric field distribution at ground level.

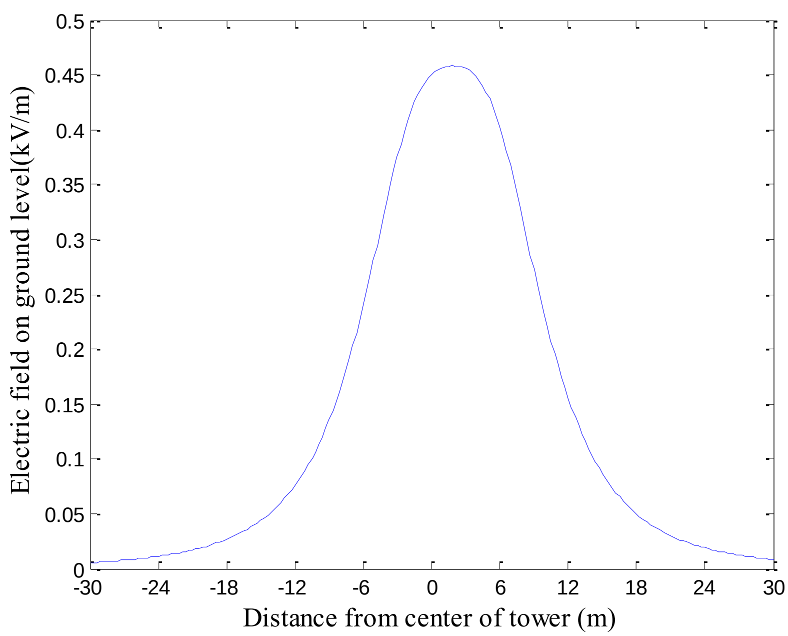


Fig. 4.3 80 kV six-phase conventional tower transmission line electric field distribution at ground level.

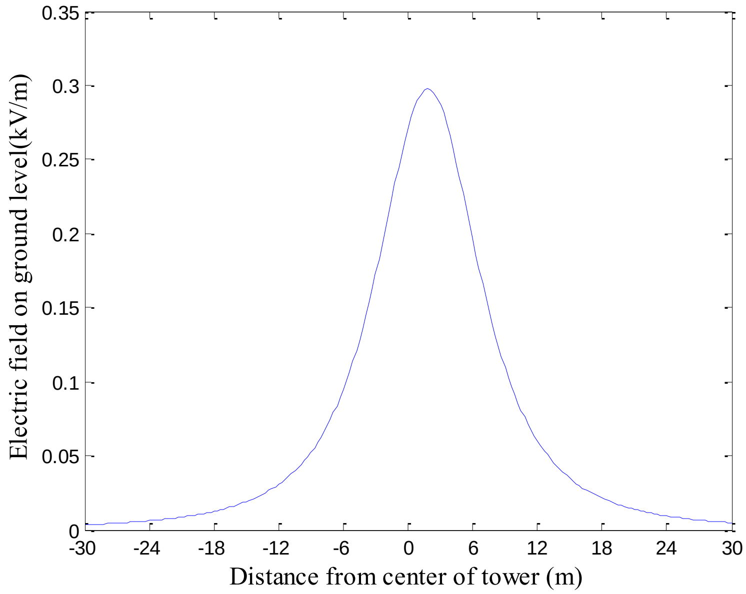


Fig. 4.4 80 kV six-phase compact tower transmission line electric field distribution at ground level.

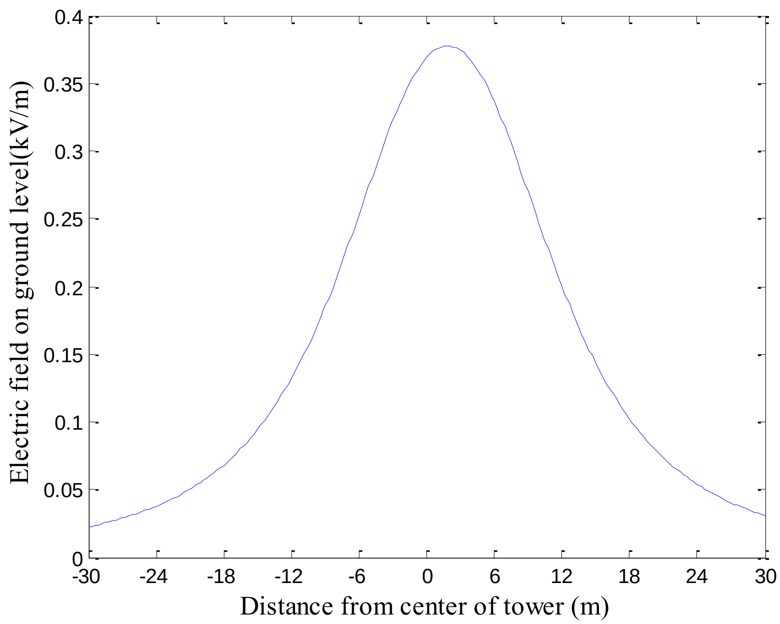


Fig. 4.5 138 kV six-phase conventional tower transmission line electric field distribution at ground level.

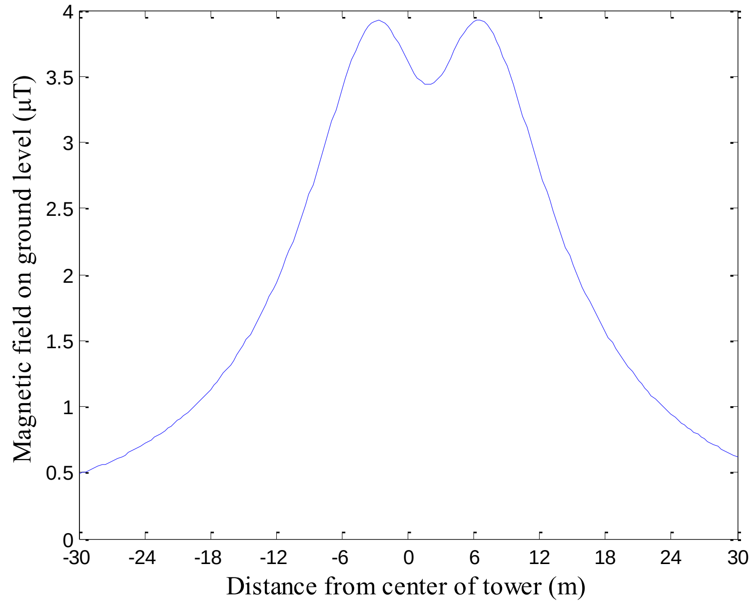


Fig. 4.6 138 kV three-phase double circuit tower transmission line magnetic field distribution at ground level.

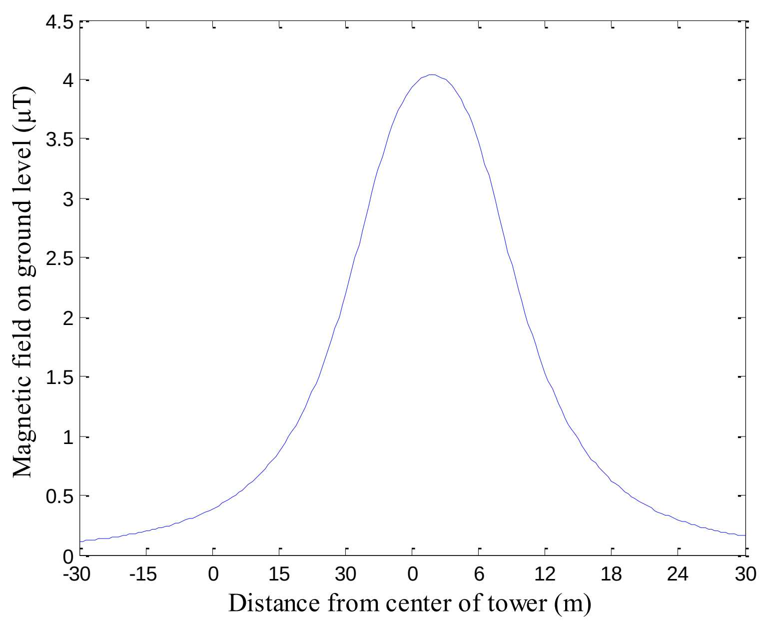


Fig. 4.7 80 kV six-phase conventional tower transmission line magnetic field distribution at ground level.

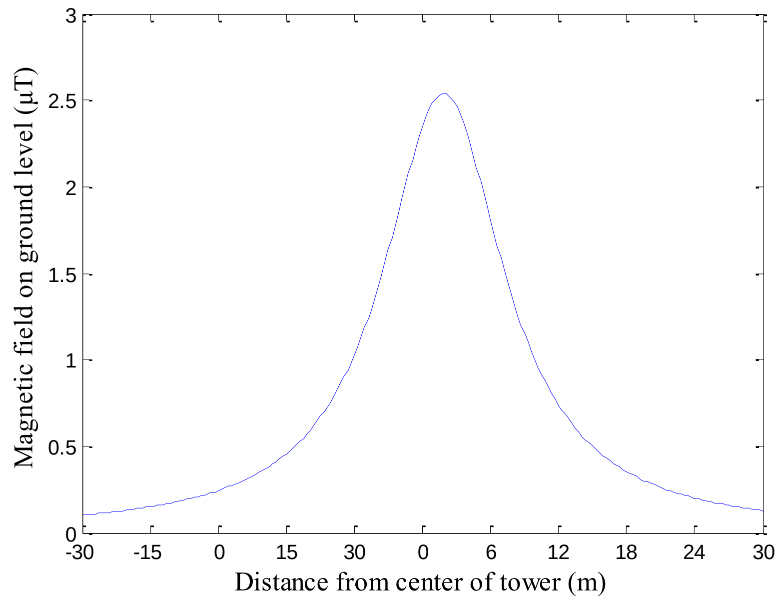


Fig. 4.8 80 kV six-phase compact tower transmission line magnetic field distribution at ground level.

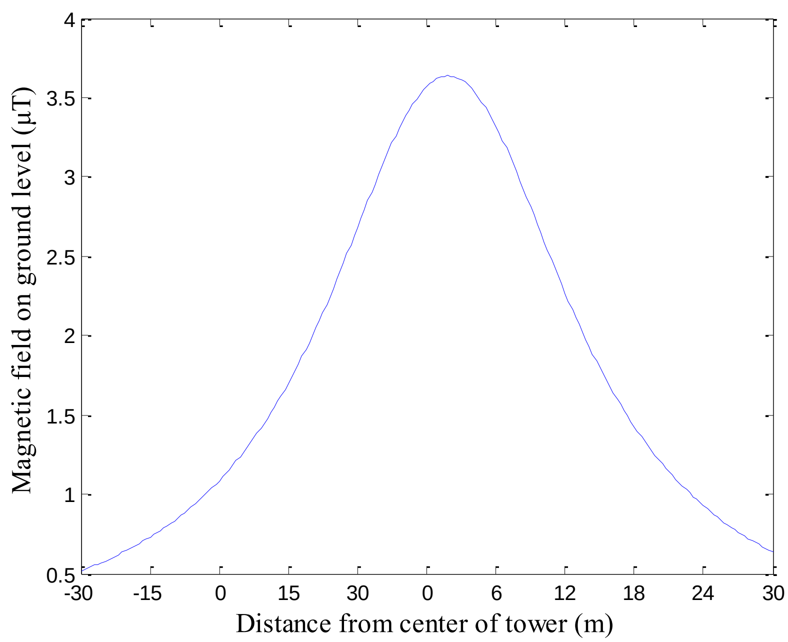


Fig. 4.9 138 kV six-phase compact tower transmission line magnetic field distribution at ground level.

TABLE 4.4
RIGHT OF WAY REQUIREMENT AND POWER TRANSFER CAPABILITY COMPARISONS

Case name	ROW requirements (m)	Power transfer capability
138 kV three-phase double circuit conventional tower line	45.7	100%
80 kV six-phase conventional tower line	36.0	100%
80 kV six-phase compact tower line	25.6	119%
138 kV six-phase conventional tower line	49.4	293%

As shown by the result in Table 4.4, with the same tower configuration, voltage level, electric and magnetic field strength at edge of right of way, the 80 kV six-phase transmission line requires about 18% less right of way. With compact tower configuration, the six-phase transmission line requires 36% less right of way and provides 19% more power transfer capability. With higher phase-to-ground voltage level and the same tower configuration, 138 kV six-phase transmission line requires only 8% more right of way, compared to 138 kV three-phase double circuit lines; while six-phase line power transfer capability increases by 193%. It demonstrates that the tower size and right of way requirements of six-phase transmission lines can be significantly compacted, while the power transfer capability can stay the same as double circuit three-phase line. In another words, six-phase line provides more power transfer capability with the same tower size and right of way requirements as three-phase double circuit line.

CHAPTER 5

SIX-PHASE FAULT ANALYSIS

There are 120 fault combinations and 23 unique fault types in a six-phase system, due to phase angle change and phase increase. There are only 5 fault types in three-phase system. For this reason, high phase order protection is much more complicated than three-phase system. Although research and field experiences have been accumulated for high phase order fault analysis and protection, it is unclear that exiting technology provides adequate protection for high phase order transmission [32]. To clarify this problem, six-phase fault analysis and six-phase transmission line protection system design are presented in this chapter and the following chapter, respectively.

5.1 Six-phase equivalent system

Many theories and research about high phase order fault analysis have been published [15], [21], [46]-[47]. The major high phase order fault analysis methods are based on symmetrical components method and phase coordinated method. Phase coordinated method was developed by S. S. Venkata, and published in 1982 [21]; this method was applied to analyze six-phase line fault in study of the six-phase demonstration project. For this reason, phase coordinated method proposed in the reference [21] was employed in six-phase fault analysis in this thesis. The details of the phase coordinated method are introduced below.

As shown in Fig. 1.2, the system containing six-phase transmission line is a three-phase and six-phase mixed system. For transmission line protection design purpose, beside the transmission line, the rest of the system can be simplified into two equivalent impedance components and two ideal sources [46]. The system in Fig. 1.2 can be represented as Fig. 5.1. Two ideal three-phase voltage sources provide power at both sides of the six-phase transmission line. Two three-phase equivalent impedances are connected between the ideal sources and the six-phase transmission line. Ideal transformers are connected between the equivalent impedance and six-phase transmission line to achieve phase-shifting.

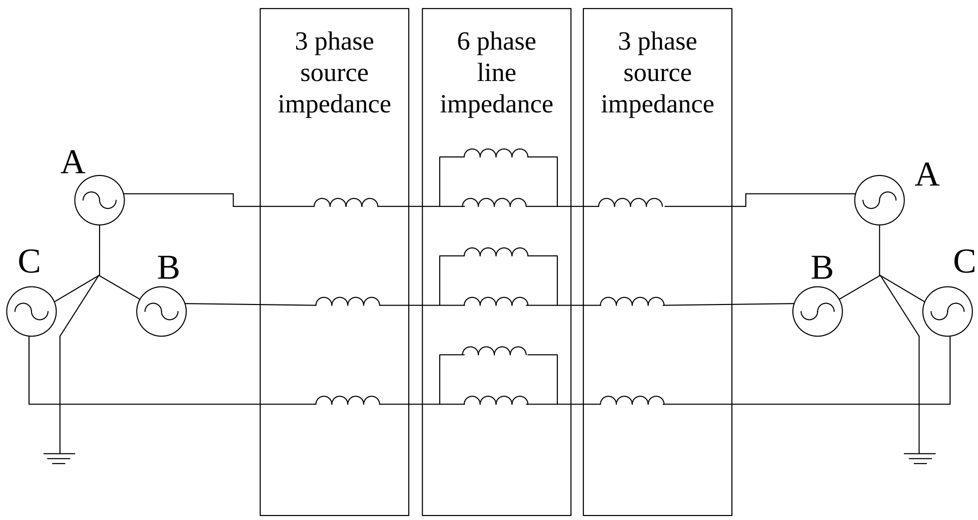


Fig. 5.1 Three-phase simplified system with six-phase transmission line network.

To employ phase coordinated method in six-phase transmission line fault analysis, the mixed system must be converted to a complete six-phase system as shown at Fig 5.2.

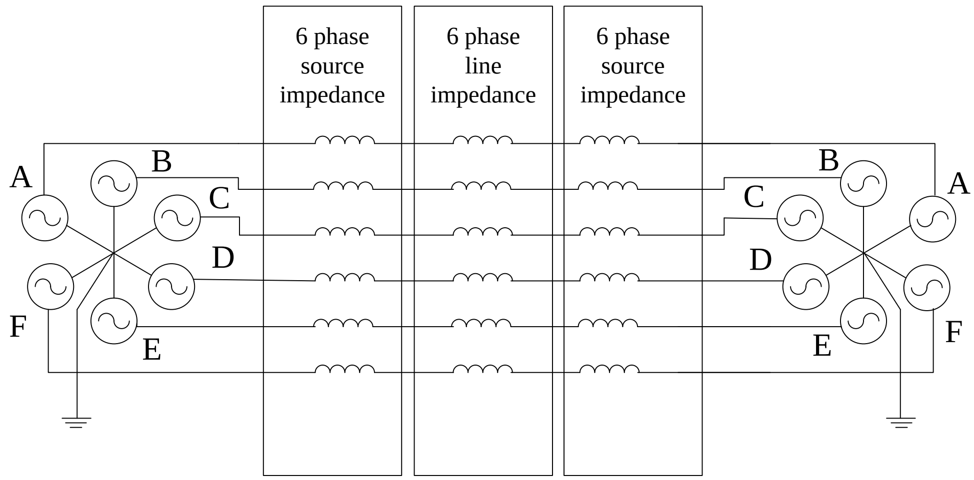


Fig. 5.2 Six-phase equivalent system network.

In Fig 5.2, voltage level of ideal sources is equal to the transmission line phase-to-ground voltage. The six-phase line impedance can be calculated by the method described in Chapter 2.1 and presented by a symmetrical 6×6 matrix. The method to calculate six-phase source impedance is described below.

To calculate three-phase equivalent source impedance, Powerworld® was used in this thesis. The original system (the system without a six-phase transmission line) can be modeled in Powerworld simulation. A 4-bus system is modeled by Powerworld® and shown in Fig. 5.3. The system configuration can be found in reference [35].

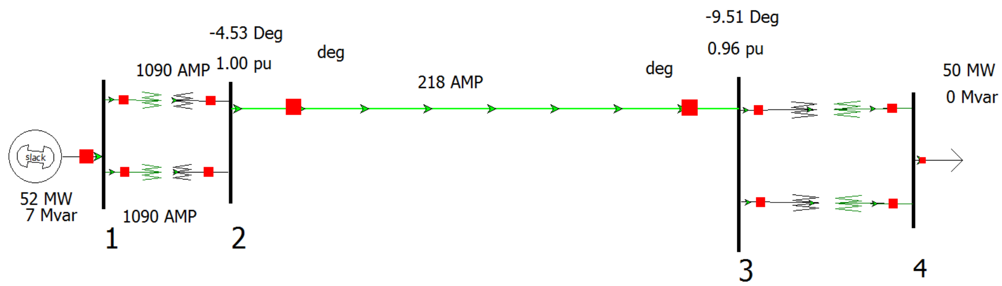


Fig. 5.3 4-bus system diagram in Powerworld model.

To calculate the three-phase equivalent source impedance at the sending end of the transmission line, a single phase-to-ground fault was set at bus 2. The voltage at fault locations and currents contributed by transformers can be calculated from Powerworld simulation and presented in sequence components as follows:

Sequence voltages at fault location:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

Sequence currents from bus 1 to bus 2:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

The equivalent source sequence impedance can be calculated as follows [21].

$$Z_1 = Z_2 = V_1 / I_1 \tag{5.1}$$

and

$$Z_0 = V_0 / I_0 \tag{5.2}$$

The three-phase impedance matrix can be calculated and presented in matrix by,

$$\boldsymbol{Z_{3p}} = \begin{bmatrix} Z_{3pself} & Z_{3pmutual} & Z_{3pmutual} \\ Z_{3pmutual} & Z_{3pself} & Z_{3pmutual} \\ Z_{3pmutual} & Z_{mutual} & Z_{3pself} \end{bmatrix} = \boldsymbol{A}^{\boldsymbol{-1}} \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \boldsymbol{A} \tag{5.3}$$

where

$$\boldsymbol{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix},$$

$$a = \frac{-1}{2} + j\frac{\sqrt{3}}{2} = 1\angle 120^o.$$

To convert the three-phase impedance matrix to an equivalent six-phase matrix. Procedure of calculating the single equivalent circuit from three-phase double circuit line should be reversed as following [35]:

It is assumed that both three-phase and six equivalent source impedance are symmetrical. The admittance matrix of equivalent source impedance can be calculated by,

$$\boldsymbol{Y_{3p}} = \boldsymbol{Z_{3p}}^{\boldsymbol{-1}} = \begin{bmatrix} Y_{3self} & Y_{3mutual} & Y_{3mutual} \\ Y_{3mutual} & Y_{3self} & Y_{3mutual} \\ Y_{3mutual} & Y_{3mutual} & Y_{3self} \end{bmatrix}. \tag{5.4}$$

Since the voltage drops on equivalent source impedance are equal, the following equations can be derived,

$$\begin{bmatrix} I_{3a} \\ I_{3b} \\ I_{3c} \end{bmatrix} = \begin{bmatrix} Y_{3self} & Y_{3mutual} & Y_{3mutual} \\ Y_{3mutual} & Y_{3self} & Y_{3mutual} \\ Y_{3mutual} & Y_{3mutual} & Y_{3self} \end{bmatrix} \begin{bmatrix} E_{3a} \\ E_{3b} \\ E_{3b} \end{bmatrix} \tag{5.5}$$

where

I_{3a}, I_{3b}, and I_{3c} are the phase current of equivalent source impedance,

E_{3a}, E_{3b}, and E_{3c} are the voltage drops on equivalent source impedance.

The equivalent six-phase impedance matrix can be represented as,

$$\boldsymbol{Z_{6p}} = \begin{bmatrix} Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} \end{bmatrix}. \quad (5.6)$$

This 6×6 matrix can present a six-phase transmission line and or a three-phase double circuit line impedance. Instead of obtaining the equivalent six-phase impedance matrix, an equivalent three-phase double circuit impedance matrix is calculated. Based on a three-phase transmission line, similar equations can be derived for the six-phase source impedance matrix as (5.4) and (5.5),

$$\boldsymbol{Y_{6p}} = \boldsymbol{Z_{6p}^{-1}} = \begin{bmatrix} Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} \end{bmatrix} \quad (5.7)$$

$$\begin{bmatrix} I_{3a1} \\ I_{3b1} \\ I_{3c1} \\ I_{3a2} \\ I_{3b2} \\ I_{3c2} \end{bmatrix} = \begin{bmatrix} Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6mutual} & Y_{6self} \end{bmatrix} \begin{bmatrix} E_{3a1} \\ E_{3b1} \\ E_{3c1} \\ E_{3a2} \\ E_{3b2} \\ E_{3c2} \end{bmatrix} \quad (5.8)$$

where

I_{3a1}, I_{3b1}, I_{3c1}, I_{3a2}, I_{3b2}, and I_{3c2} are the phase currents of equivalent three-phase double circuit impedance,

E_{3a1}, E_{3b1}, E_{3c1}, E_{3a2}, E_{3b2}, and E_{3c2} are the voltage drops on equivalent three-phase double circuit impedance.

Equation (5.5) can be represented as:

$$\begin{bmatrix} I_{3p1} \\ I_{3p2} \end{bmatrix} = \begin{bmatrix} Y_A & Y_B \\ Y_C & Y_D \end{bmatrix} \begin{bmatrix} E_{3p1} \\ E_{3p2} \end{bmatrix} \tag{5.9}$$

where

$$\boldsymbol{Y_A} = \boldsymbol{Y_D} = \begin{bmatrix} Y_{6self} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6self} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6self} \end{bmatrix},$$

$$\boldsymbol{Y_B} = \boldsymbol{Y_C} = \begin{bmatrix} Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \\ Y_{6mutual} & Y_{6mutual} & Y_{6mutual} \end{bmatrix},$$

Since the equivalent three-phase double circuit line is completely transposed, the currents and voltage drops on both circuits are identical. Equation (5.9) can be simplified as,

$$\begin{bmatrix} I_{3p1} \\ I_{3p1} \end{bmatrix} = \begin{bmatrix} Y_A & Y_B \\ Y_C & Y_D \end{bmatrix} \begin{bmatrix} E_{3p1} \\ E_{3p1} \end{bmatrix}. \tag{5.10}$$

Adding I_{3p1} and I_{3p2},

$$(I_{p1} + I_{p1}) = (Y_A + Y_B + Y_C + Y_D)E_{p1}. \tag{5.11}$$

Equation (5.9) can be represented as,

$$\begin{bmatrix} 2I_{3a1} \\ 2I_{3b1} \\ 2I_{3c1} \end{bmatrix} = \begin{bmatrix} 2(Y_{6self}+Y_{6mutual}) & 4Y_{6mutual} & 4Y_{6mutual} \\ 4Y_{6mutual} & 2(Y_{6self}+Y_{6mutual}) & 4Y_{6mutual} \\ 4Y_{6mutual} & 4Y_{6mutual} & 2(Y_{6self}+Y_{6mutual}) \end{bmatrix} \begin{bmatrix} E_{3a1} \\ E_{3b1} \\ E_{3c1} \end{bmatrix}. \quad (5.12)$$

Since the original three-phase impedance is equivalent to the double circuits impedance, (5.5) is identical with (5.12). The following equations can be derived,

$$Y_{3self} = 2(Y_{6self} + Y_{6mutual}) \quad (5.13)$$

$$Y_{3mutual} = 4Y_{6mutual} \quad (5.14).$$

By solving (5.13) and (5.14), the six-phase equivalent source impedance matrix can be constructed with equation (5.6).

The same procedures can be executed for calculating the six-phase equivalent source impedance at the receiving end.

5.2 Six-phase fault analysis method

Based on the equivalent system shown in Fig. 5.2, six-phase transmission line fault analysis can be conducted in following manner [21].

(1). six-phase source voltages are represented as,

$$\boldsymbol{E} = \begin{bmatrix} E_a \\ E_b \\ E_c \\ E_d \\ E_e \\ E_f \end{bmatrix} \quad (5.15)$$

where

$$E_b = b^5 E_a, E_c = b^4 E_a, ...E_f = bE_a,$$

$$b = 0.5 + j\ 0.866 = 1\angle 60^o .$$

$$\boldsymbol{V} = \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \\ V_f \end{bmatrix} . \tag{5.16}$$

(2). Based on the model shown in Fig. 5.2, following equation can be derived,

$$\begin{bmatrix} E_a - V_a \\ E_b - V_b \\ E_c - V_c \\ E_d - V_d \\ E_e - V_e \\ E_f - V_f \end{bmatrix} = \begin{bmatrix} Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \\ I_f \end{bmatrix} . \tag{5.17}$$

6×6 matrix is Thevenin impedance matrix from bus to source.

(3). Set an appropriate boundary condition in (5.17) and solve the equation. Take a single phase ground (phase A to ground fault) for an example,

$$\begin{bmatrix} E_a - 0 \\ E_b - V_b \\ E_c - V_c \\ E_d - V_d \\ E_e - V_e \\ E_f - V_f \end{bmatrix} = \begin{bmatrix} Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} & Z_{6mutual} \\ Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6mutual} & Z_{6self} \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} . \tag{5.18}$$

In (5.18), voltages at fault location and fault currents are unknown variables to be calculated. Six unknown variables in six equations can be solved without doubt.

5.3 Fault analysis cases

In this section, three systems were selected and upgraded into six-phase transmission lines. Six-phase fault analysis was studied on the upgraded transmission lines. A program developed using MATLAB code was used to calculate the equivalent impedance and fault currents described in section 5.1 and 5.2. Additionally, upgraded transmission lines were reconfigured into three-phase double circuit lines in the systems. For both three-phase double circuit lines and six-phase transmission lines, it was assumed that same tower configuration, phase-to-ground voltage, and transmission line length were employed. Three-phase fault analysis was studied in the three-phase double circuit line. PSCAD® was used to calculate fault currents in the three-phase double circuit line.

(1) 4-bus system

A 4-bus system was modeled by Powerworld® and the system data can be found in reference [35]. The system diagram is shown in Fig. 5.3. Fault locations are selected at bus 2, 3 and middle of the transmission line. The results of six-phase fault currents are listed at Appendix A1.1- A1.3. The 4-bus system with three-phase double circuit line was modeled by PSCAD® and shown in Fig. 5.4.

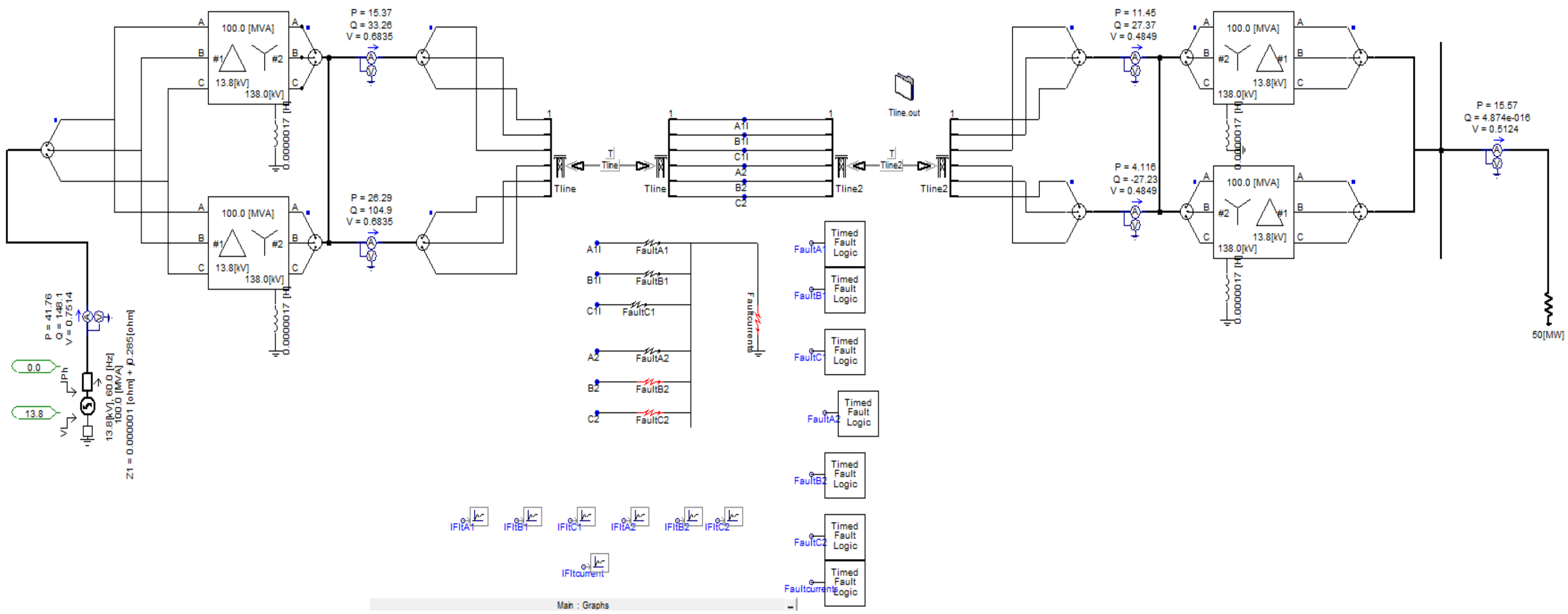


Fig. 5.4 4-bus system diagram in PSCAD model.

In the system with the three-phase double circuit line, the same fault combinations were set as in the system with the six-phase transmission line. For an example, the A1-A2-B1-C1 fault in the three-phase double circuit line was considered as the same fault type as A-C-E-D fault in the six-phase transmission line. Three fault locations in the three-phase double circuit line was selected as in the six-phase transmission line case. The results of three-phase double circuit line fault currents are listed in Appendix A1.4-1.6.

(2) 9-bus system

A 9-bus system from Powerworld® was selected for fault current analysis and the system data can be found in reference [48]. The 9-bus system diagram is shown in Fig. 5.5. Branch 7-5, which is the most heavily loaded line in the system, was replaced by a six-phase transmission line. Fault locations are selected at the both ends and the middle of the transmission line. The 9-bus system with a three-phase double circuit line was modeled by PSCAD® and shown in Fig. 5.6.

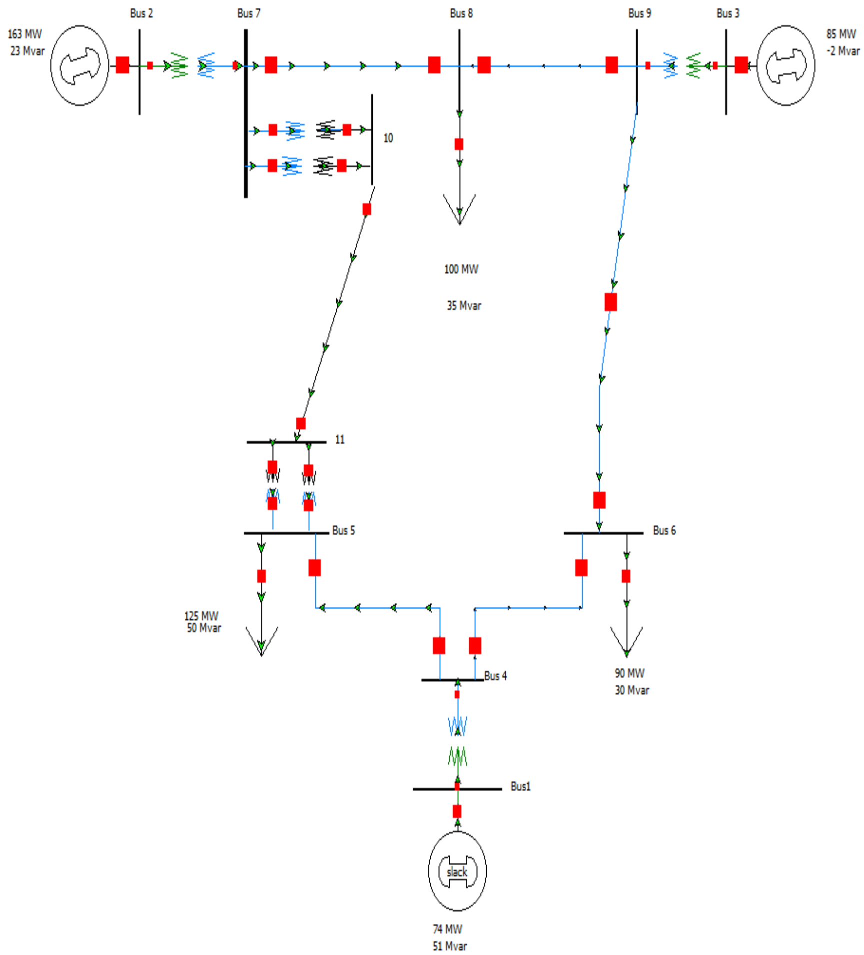


Fig. 5.5 9-bus system diagram in Powerworld model.

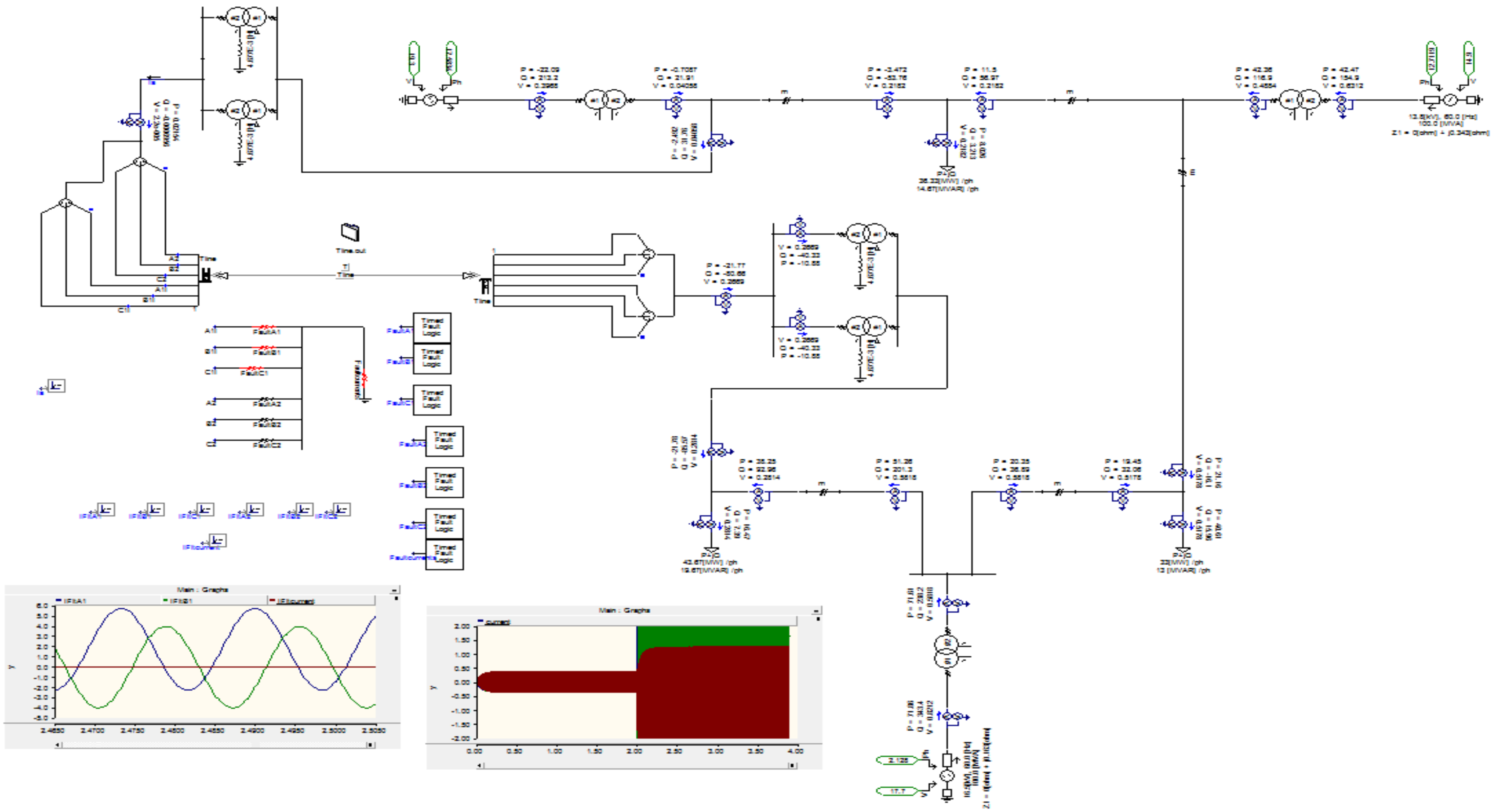


Fig. 5.6 9-bus system diagram in PSCAD model.

The results of six-phase and three-phase double circuit line fault currents are listed in Appendix A2.1- A2.6.

(3) 118-bus system

A 118-bus system from Powerworld® was selected. Six of the most heavily loaded branches were replaced with six-phase transmission lines respectively.

The zoom-in diagrams of six-phase lines in 118-bus system are shown at Figs. 5.7-5.12 at following.

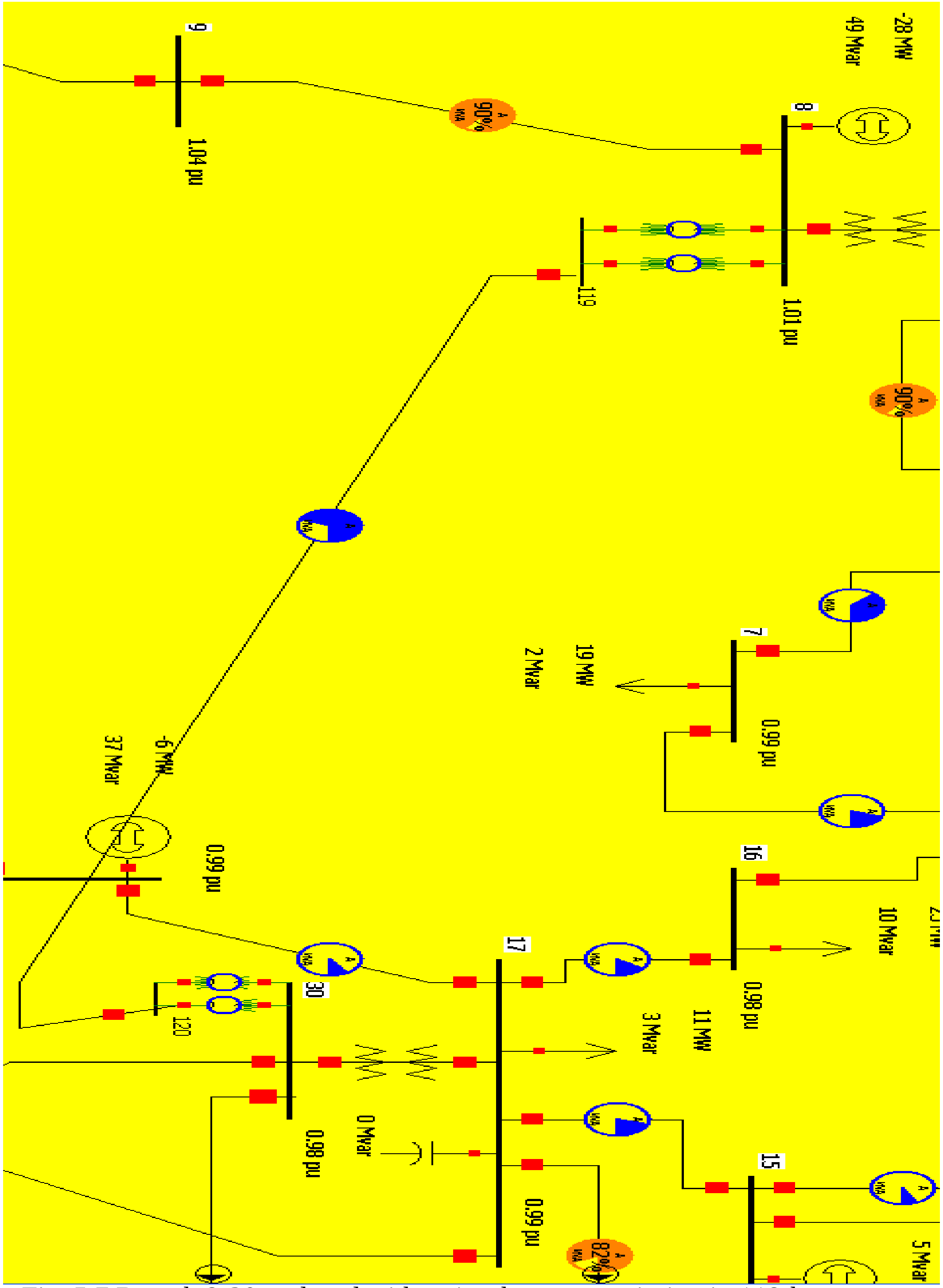


Fig. 5.7 Branch 8-30 replaced with a six-phase transmission in 118-bus system.

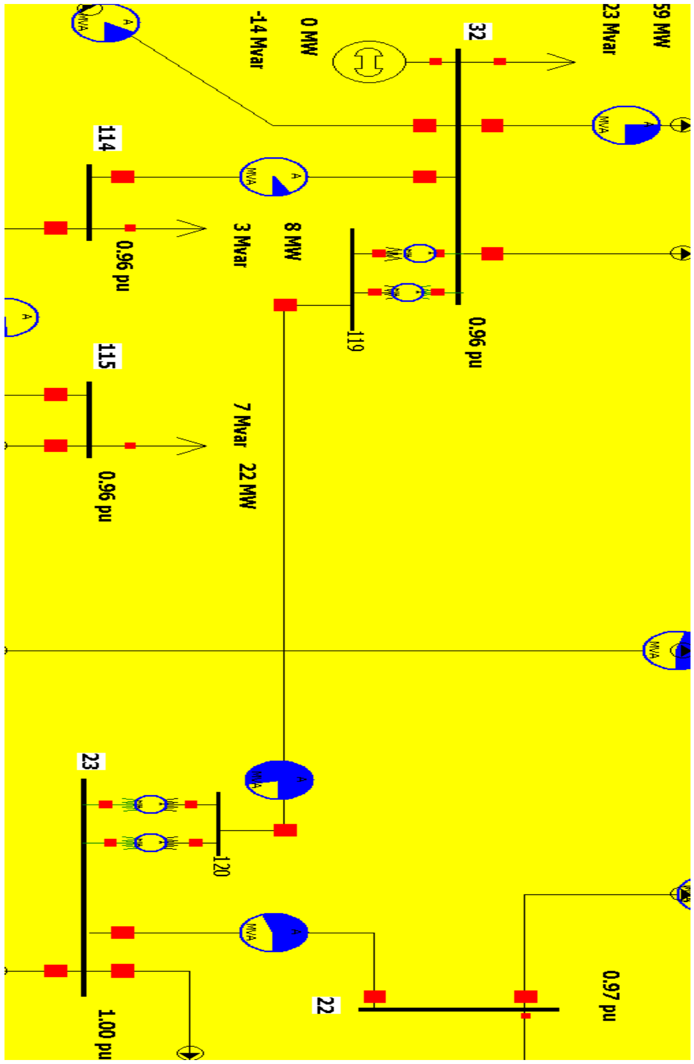


Fig. 5.8 Branch 23-32 replaced with a six-phase transmission in 118-bus system.

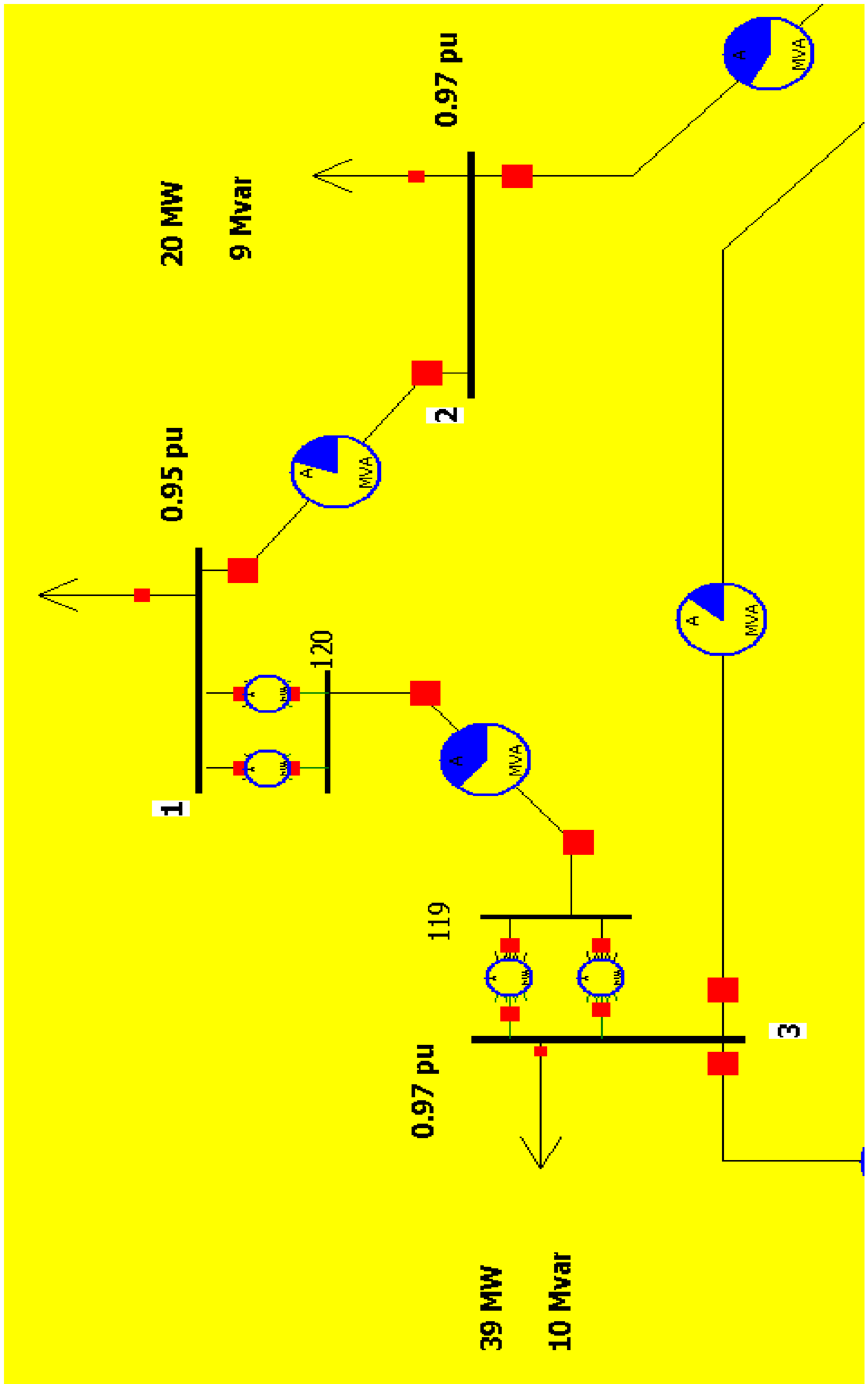


Fig. 5.9 Branch 1-3 replaced with a six-phase transmission in 118-bus system.

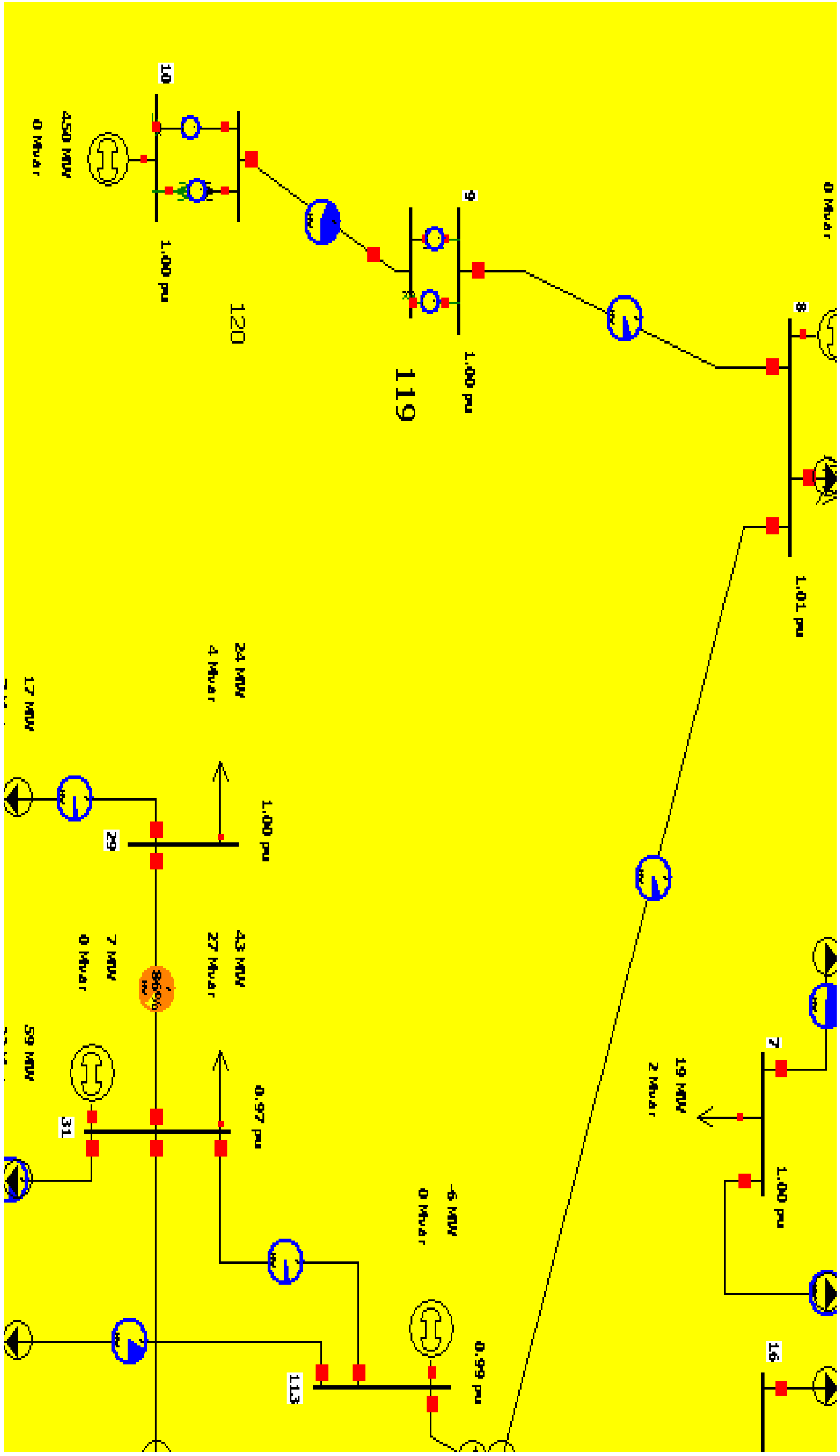


Fig. 5.1 Branch 9-10 replaced with a six-phase transmission in 118-bus system.

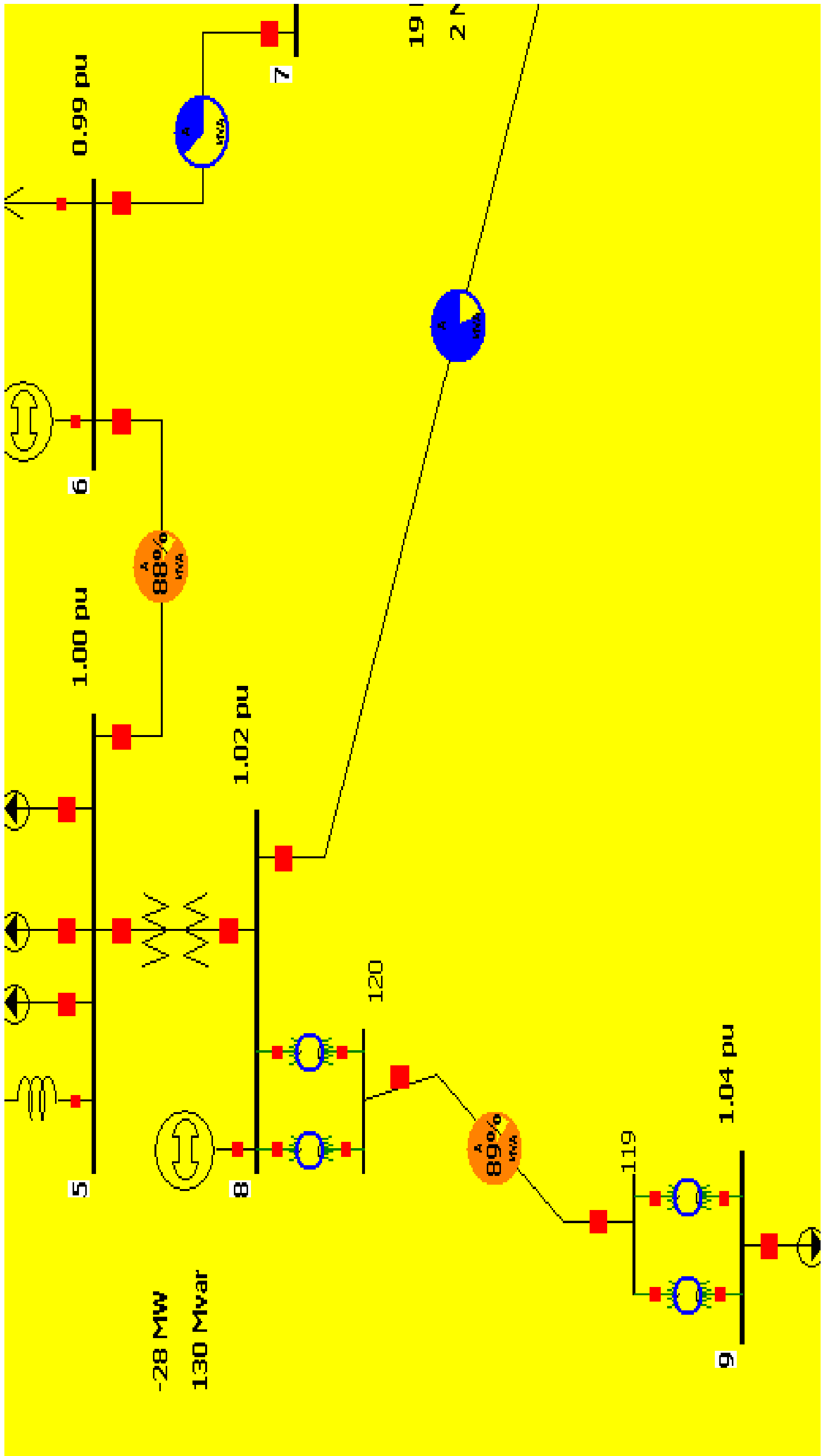


Fig. 5.2 Branch 8-9 replaced with a six-phase transmission in 118-bus system.

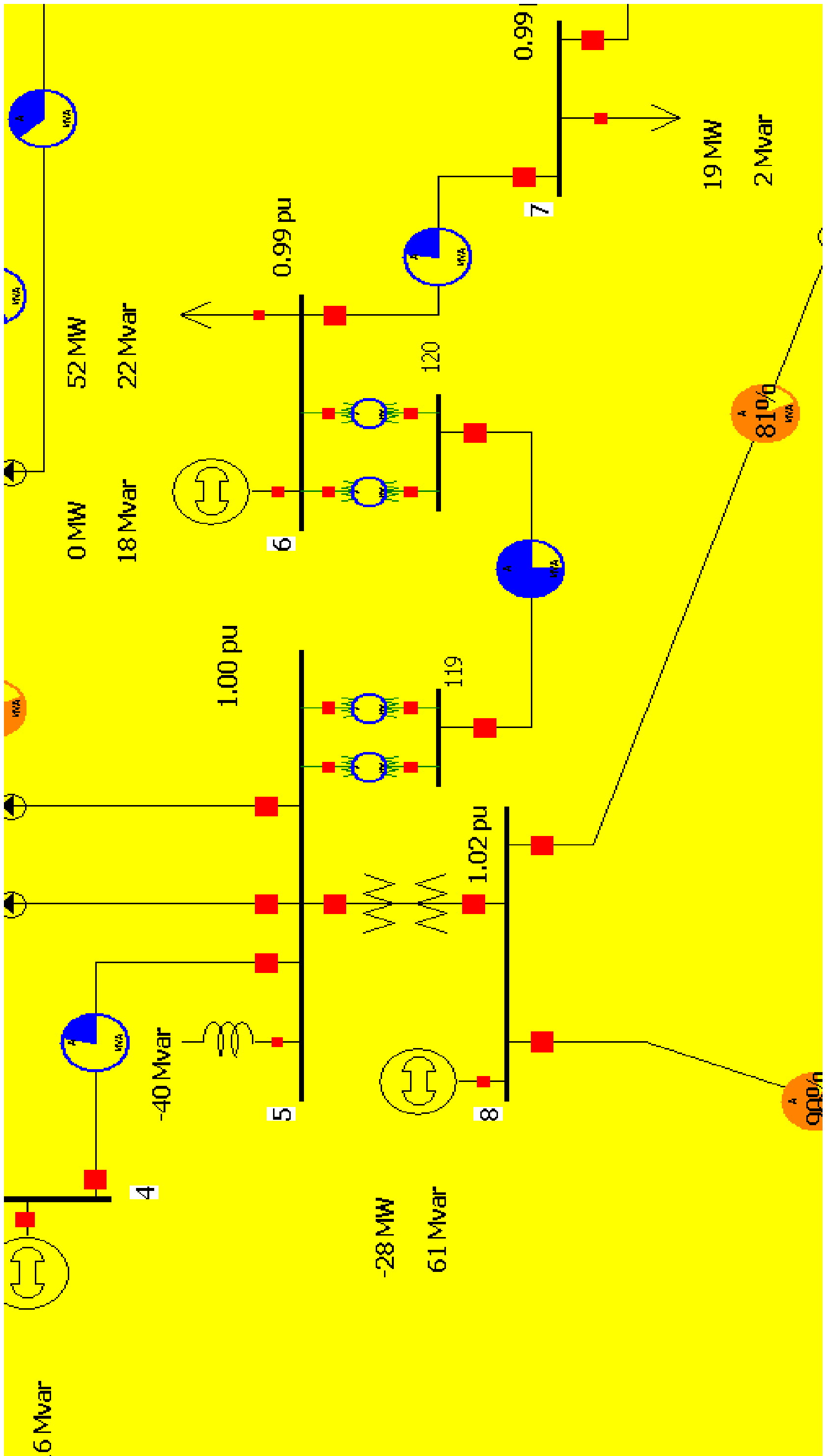


Fig. 5.3 Branch 5-6 replaced with a six-phase transmission in 118-bus system.

Six-phase faults were set at the both ends and middle of the six-phase transmission line respectively. The fault currents results are listed in Appendix A3.1-A3.18. Considering the complexity of 118-bus system and limited time, the system with three-phase double circuit lines were not simulated and calculated by PSCAD model as was the previous system.

The fault analysis results in Appendix A shown, the faults in six-phase system are more complicated, compared to three-phase system. The total six-phase fault types are 23, while there are only 16 fault types in three-phase double circuit line (considering one fault location). The results show that the ratios between maximum and minimum fault currents in six-phase lines are higher, compared to the three-phase system. As a result of fault analysis at bus 7 in 9-bus system shows, the ratios of maximum to minimum fault currents (for each conductor) are 8.7 and 3.3 for a six-phase line and a three-phase double circuit line, respectively. The high deviation of six-phase fault current requires more considerations for six-phase transmission line protection design and relay programming. However, as the results show, most fault currents in six-phase faults are lower, compared to the same faults in the three-phase double circuit lines.

CHAPTER 6

PROTECTION DESIGN

As discussed and results shown in previous chapters, whether today's relays and associated protection schemes provide enough protections for six-phase transmission lines has been debated for long period [32]. To provide the feasibility of six-phase transmission lines, research on six-phase line protection has been conducted. Some of the outcomes were employed in the six-phase demonstration line at New York [25], [49]-[51]. To examine the six-phase transmission line protection issue, a six-phase transmission line and a three-phase double circuit line, will be operated in a 4-bus system respectively. The protection systems for both lines will be designed and compared. Additionally, based on previous research, a new external relay tripping logic has been designed and described in this chapter.

6.1 Protection principles and schemes

Three-phase double circuit line protection issue has been studied for its complexity and mutual coupling [46], [52]-[54]. Difficulties of three-phase double circuit lines are caused by the following factors: (1) mutual coupling between circuits; (2) dynamic change of the characteristics of power system; (3) fault phase selection when the fault happens between double circuits [53]-[54]. These characteristics demand more requirements and considerations for three-phase double circuit protection system. It should be noted that six-phase transmission lines also possess those characteristics as three-phase double circuit lines do. Based on the previous research and experience of three-phase double circuit line protection, some transmission line protection schemes will be presented in this chapter.

(1). Segregated phase comparison

The concept of phase comparison relay protection has been applied for transmission line for many years [47]. The concept of phase comparison is that relays at both transmission line ends, record the phase currents at a specified time, and send the results to the opposite end relay. The relays determine whether the line should be tripped by comparing the stored currents data from both ends. In different types of phase comparison schemes based on this concept, segregated phase comparison scheme is selected based on its advantages in this thesis. Segregated phase comparison provides following advantages [47].

(1) Instantaneous clearing of the faults involving both lines

(2) Immunity from mutual coupling effects

(3) Fault phase selective for all types of single and multiple faults

The operation of segregated phase comparison system is described for an internal and an external transmission line faults shown in Figs. 6.1 and 6.2 [47],

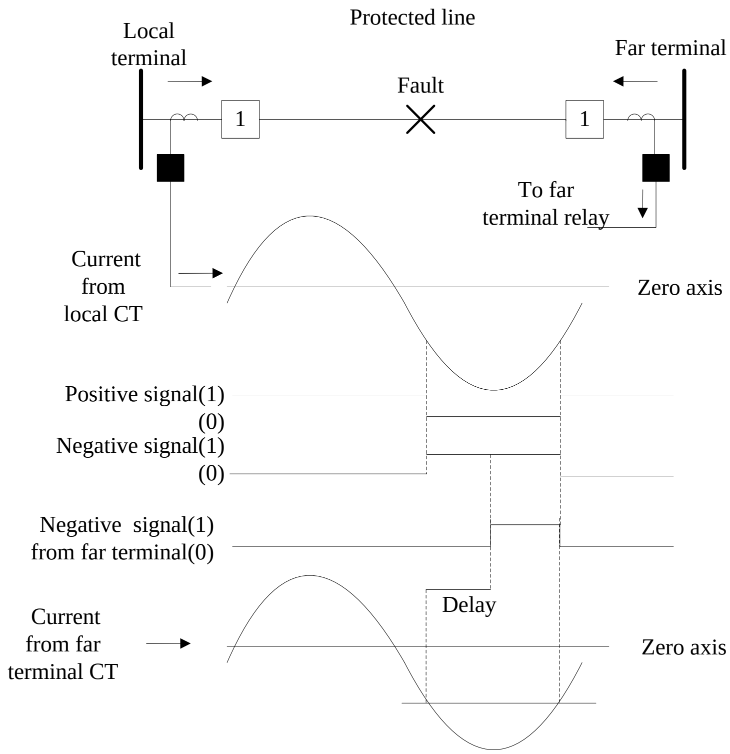


Fig. 6.1 Relay logic signals for an internal fault.

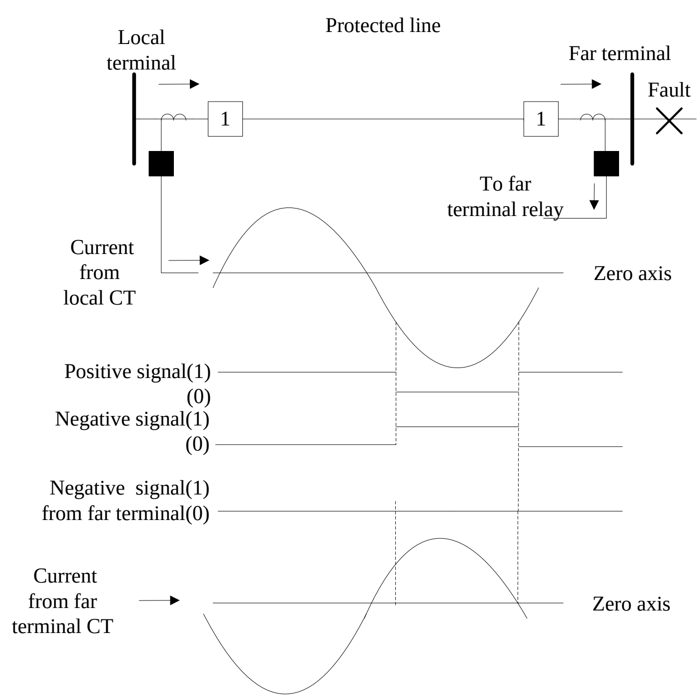


Fig. 6.2 Relay logic signals for an external fault.

As shown in Figs. 6.1 and 6.2, once a fault occurs in the system and phase current exceeds the threshold value, positive trip signal is set to 1(if the fault occurs in a positive cycle) and sent to the opposite end relay. The remote trip signal is compared to the local relay trip signal. If both signals are equal, it means the currents at both ends are flowing into the transmission line, and the faults location is in the transmission line. Both relays trip the line immediately. If the signals from both ends are not equal, the result indicates that the high phase current is due to the faults outside the transmission line. Then, the relays will not trip the line. More details of segregated phase comparison scheme are available in reference [47].

(2). Current differential relay

Current differential relay was originally developed for transformer and generator protection, and successfully extended to transmission line protection [56]-[58]. With increasing applications of digital communicational channel, the interest on current differential relay is greater than before [56]. Compared to other relays, current differential relay has many advantages. The simplicity of the scheme and setting is a one of the most significant advantages [56]. Current differential relay operation principle is described below.

A typical connection of current differential relay is shown in Fig. 6.3.

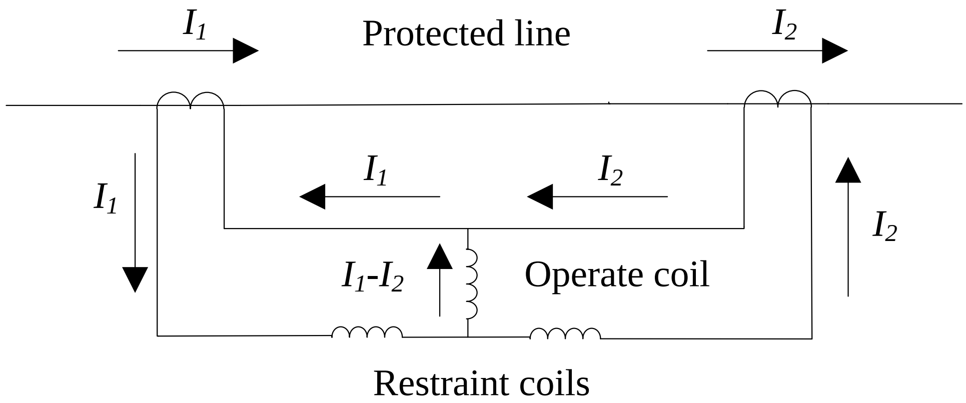


Fig. 6.3 Typical connection of current differential relay.

As shown in Fig. 6.3, the currents through both ends of the transmission line are measured by current transformers; the relay operation is determined by the differential of the currents from both ends. If a fault occurs outside the transmission line, both currents I_1 and I_2 flow in the same direction, and differential current is equal to zero, the relay will remain blocked. If a fault occurs in a transmission line, both currents I_1 and I_2 flow in the opposite directions, the differential current is greater than zero. The relay will trip the protected line. In practical applications, current measurements are usually influenced by the system's noises and measurement devices errors. To eliminate this impact, restraining coils are installed in the circuits. The restraining coil is a settable device determining the tripping area of current differential relays, which shown in Fig. 6.4

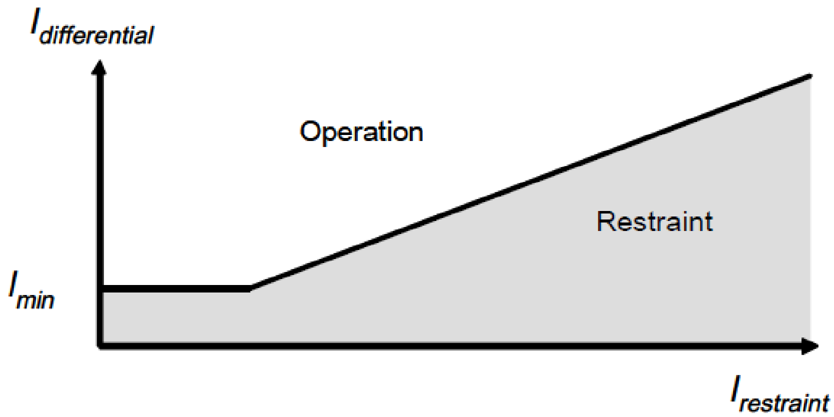


Fig. 6.4 Stabilized characteristic of the current differential relay [56].

Generally, the 50% setting rule is applied for simplicity. Thus, restraint characteristic is commonly set to 50%. The curve slope in Fig. 6.4 is *k*=1. Additionally, a pick-up setting of 50% of minimum fault current was recommended. The fault current is the sum of the currents from the two line ends. More details on current differential relay are available in the reference [47].

(3). Directional comparison blocking scheme

Similar as two schemes above, directional comparison blocking scheme is a plot protection system which depends on communication channel. Directional comparison blocking scheme is developed based on distance relay, which is distinct from two schemes above. The operations of directional comparison blocking scheme is described as below.

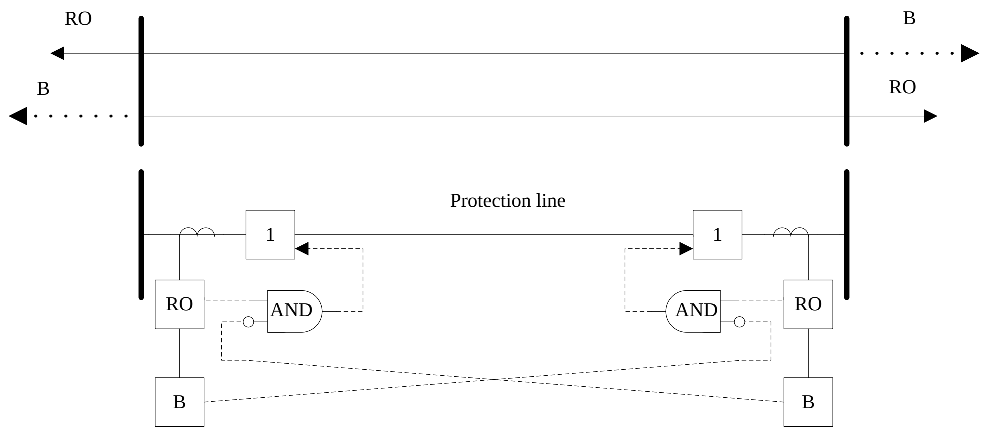


Fig. 6.5 Directional comparison blocking scheme.

As shown in Fig. 6.5, an overreaching tripping device (RO) and blocking device (B) are installed at both ends of the protected transmission line. The overreaching tripping devices are developed from directional distance relays, and set protection areas covering 120-150% of the transmission line length. If an external fault occurs at 110% of the transmission zone, the overreaching tripping device at one transmission line end detects the fault and a tripping signal is sent to AND functions. However, the blocking device at opposite end is not trigger, and no block signal is received at the end. The AND function does not operate with only one trigger signal from the overreaching tripping device. If an internal fault occurs in the protected zone, overreaching tripping devices at both ends detect the fault and send a signal to AND function and blocking device. The block devices send a signal to opposite ends via the communication channel. The signal from opposite end blocking device is reversed and sent to AND function. AND functions at both ends generate a signal to trip the transmission lines.

6.2 Three-phase double circuit transmission line protection design and setting

A three-phase double circuit in a 4-bus system is selected for transmission line protection design. The system diagram is shown in Section 5.2 and the details of the system are specified in reference [35]. According to reference [33], the transmission line is classified as a medium length line. Segregated phase comparison scheme and current differential relay are selected as the primary and secondary protection system. For the backup protection system, it must be coordinated with upstream and downstream protection system settings. Since limited information about the upstream and downstream protection system is available, the backup system design is not included in this chapter. For both primary and secondary protection, microwave communication channel is selected. External trip logic must be designed to coordinate the fault phase selection. The protection configurations are shown in Fig. 6.6,

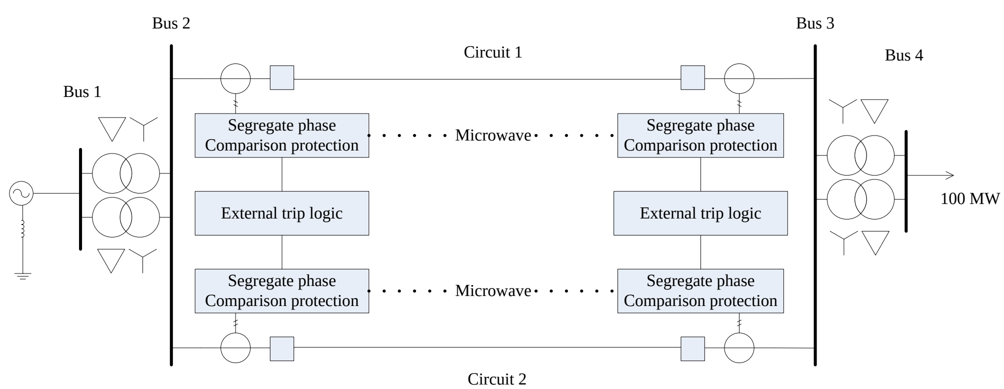


Fig. 6.6 Three-phase double circuit line protection system in a 4-bus system.

The configuration selection and setting calculation procedure is described as below.

It is assumed that power generated at under maximum load condition is P=100 MW.

Based on Powerworld simulation results, the maximum load currents of each conductor at the sending and receiving ends of transmission line are I_{smax}= 218A and I_{rmax}= 218A. The following configurations are selected and calculated.

Current transformers ratio: 250:5

Line charging current: 0.1/50=0.001 A

Maximum Load currents at secondary side:

I_{max}/CT_{ratio}=218/50=4.36 A

According to reference [56], segregated phase comparison scheme protection settings at secondary side are calculated as below:

LPKY: Local phase pickup for enabling the transmitter keying circuit

LPKY =2.7 A

RPKY: Remote phase pickup for enabling the transmitter keying circuit

RPKY = 3.0 (4.36/5) =2.62 A

With relay settings calculated above, the segregate phase comparison protection system will start to compare the phase currents when the transmission line phase current is over 135 A at the primary side.

Current differential relays generally recommend a pick-up setting of 50% of minimum fault current. The fault current is the sum of the currents from the both ends of the line [56]. In this thesis, Powerworld fault analysis simulation is used to calculate the minimum fault current. The minimum fault current occurs when a single phase-to-ground fault is set at the 40% of the line location at circuit one. The value of the minimum fault current is

$$I_{fmin}= 1378\angle -85.26^{o}\ \mathrm{A}$$

The minimum operating threshold of current differential relay setting is

$$I_{op}=1378/2=689\mathrm{A}$$

With fault currents calculated above, current differential relay will start to compare the phase currents from both ends, when the phase current is over 689A.

To coordinate the relay operations in both circuits, external trip logic was designed for fault phase selection and shown in Fig. 6.7,

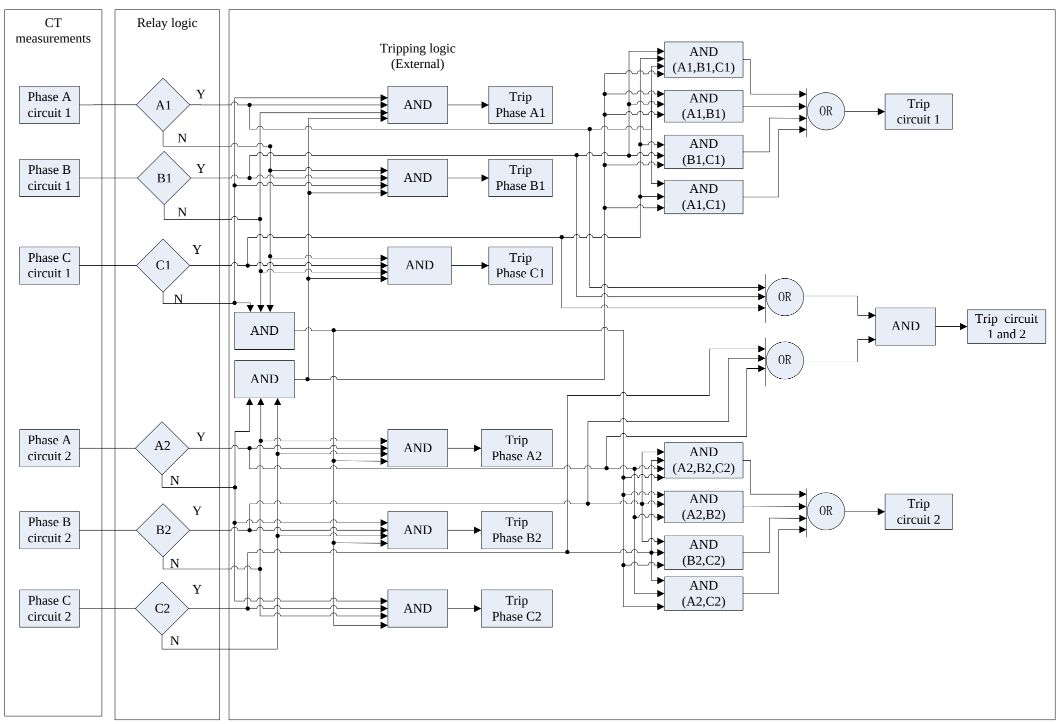


Fig. 6.7 External trip logic for a double circuit line protection.

6.3 Six-phase transmission line protection design

In this section, the same 4-bus system was selected as in Section 6.2. All the system data and transmission line configurations are the same as in section 6.2.

The only difference is that the transmission line between bus 2 and 3was reconfigured to a six-phase transmission line. The system diagram is shown in Fig. 6.8,

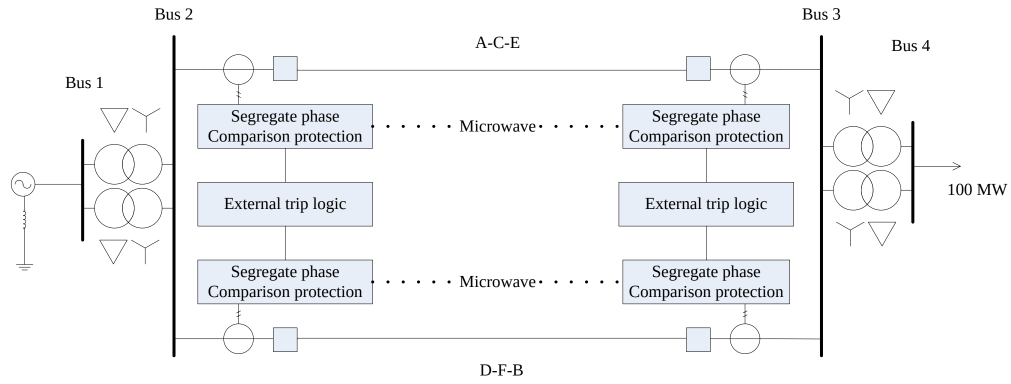
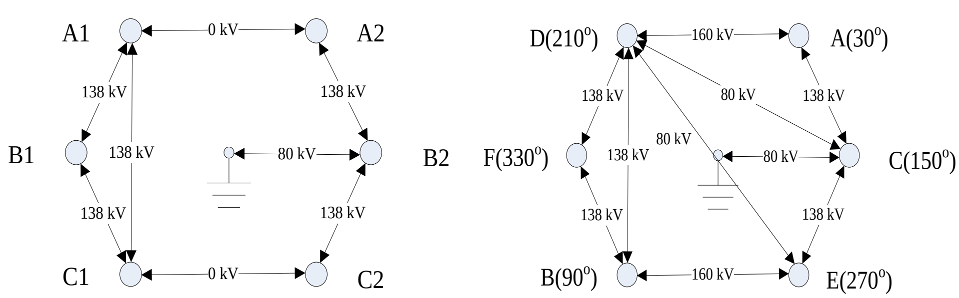


Fig. 6.8 4-bus system diagram with a six-phase transmission line.

In Fig. 6.9, conductor and phase arrangements of three-phase double circuit and six-phase line are shown,



(a). Three-phase double circuit line (b). Six-phase line

Fig. 6.9 Conductor and phase arrangements of three-phase double circuit and six-phase line.

As shown in Fig. 6.9, the conductors in the six-phase transmission line can be classified into two groups: (1) A-C-E and (2) D-F-B [51].These two groups are similar as the groups in the three-phase double circuit line. The only difference is that the phase in two groups is not equal as that in the three-phase double circuit line. This difference does not influence the six-phase protection design.

Similar to the three-phase double circuit line in Section 6.2, the six-phase transmission line protection was designed. According to reference [46], the transmission line is classified as a medium length line. Segregated phase comparison scheme and directional comparison blocking scheme were selected as the primary and secondary protection system. It should be noted that, current differential relay pick-up currents setting is usually set as 50% of minimum current, but over maximum load current for reliability purpose [33]. In the 4-bus system, phase A fault current is 220 A under an A-B-F fault. If the pick-up current of the current differential relay is set as 50% of minimum fault current in this case, current differential relays may mis-operate and trip the line with unbalanced load. The backup protection system must be coordinated with upstream and downstream protection system settings. Since limited information about the upstream and downstream protection system is available, the backup system design is not included in this chapter. For both primary and secondary protection, a microwave communication channel is selected. External trip logic must be designed to coordinate the fault phase selection.

It is assumed that power generated at under maximum load condition is P=100 MW.

Based on Powerworld simulation results, the maximum load current of each conductor at the sending and receiving ends of the transmission line are

I_{smax}= 218 A and I_{rmax}= 218 A. The following configurations are selected and calculated.

Current transformers ratio: 250:5

Voltage transformer ratio: 2000:1

Line charging current: 0.1/50=0.001 A

Maximum load currents at secondary side:

I_{max}/CT_{ratio}=218/50=4.36 A

According to reference [56], segregated phase comparison scheme protection settings are calculated as below:

LPKY: Local phase pickup for enabling the transmitter keying circuit

LPKY =2.7

RPKY: Remote phase pickup for enabling the transmitter keying circuit

RPKY = 3.0 (4.36/5) =2.62 A

With relay settings calculated above, the segregate phase comparison protection system will start to compare the phase currents when the transmission line phase current is over 135 A at primary side.

Directional Comparison Blocking settings are calculated as follows.

1. Ground impedance relay

$$Z_a' = \frac{\frac{1}{2000} \times V_1}{\frac{5}{250} \times I_1} = \frac{Z_a}{40}$$

Protecting distance is set as 120% of the line length. Based on the results of fault current analysis, the positive sequence impedance of the line is,

$$Z_1 = 120.55 + j177.85\Omega.$$

The protecting zone:

$$Z_{r120\%} = Z_a = (120.55 + j177.85) \times 1.2 = 144.66 + j213.42\Omega$$

$$Z_a' = \frac{144.66 + j213.42}{40} = 3.616 + j5.335 = 6.455\angle 55.87^o \Omega$$

2. Phase impedance relay

Phase impedances are measured as follows.

$$Z_a = \frac{V_a - V_c}{I_a - I_c} = \frac{V_a - V_e}{I_a - I_e} = \frac{V_c - V_e}{I_c - I_e}$$

To coordinate the relay operations, external trip logic was designed for fault phase selection and shown in Fig. 6.10.

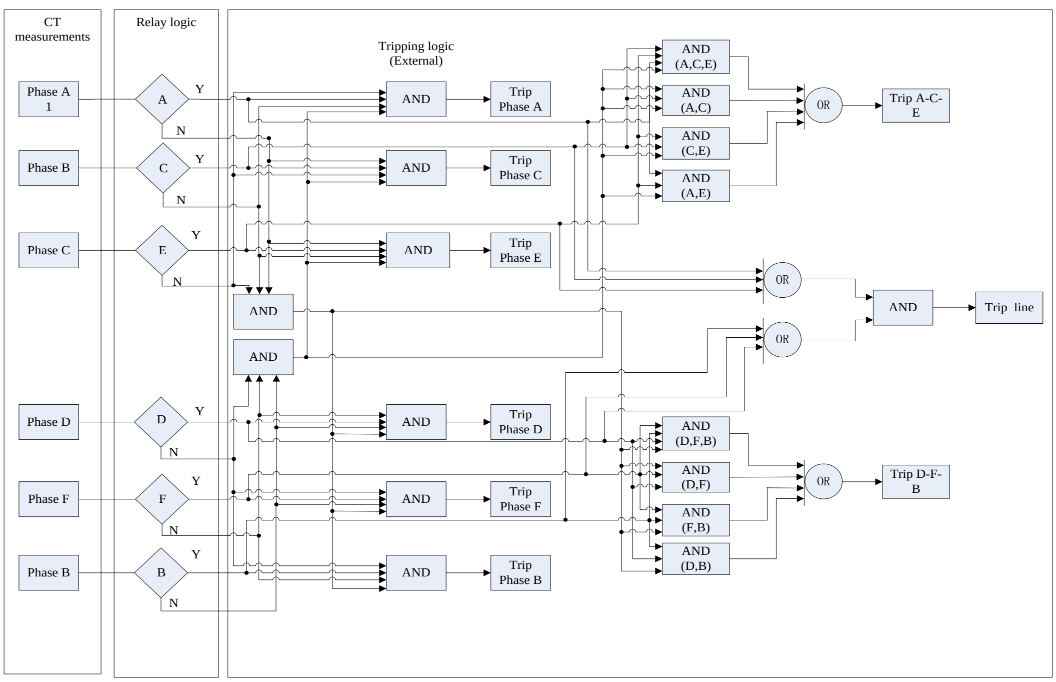


Fig. 6.10 External trip logic for a six-phase transmission line protection.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusions

The research objective work is evaluating and comparing the advantages of three-phase double circuit and six-phase transmission line. For evaluation and comparison, four transmission line cases, one three-phase double circuit, and three different six-phase transmission lines, were selected. Transmission line parameters, power transfer capability, electric field, magnetic field, and right of way, were selected as evaluation criteria. A program developed using MATLAB code, was used to calculate performances of the four proposed cases on the selected criteria.

Additionally, to clarify the doubts about six-phase transmission line protection, fault analysis on three-phase double circuit line, and six-phase transmission line, were studied in three systems. Based on the fault currents, a three-phase double circuit transmission line protection system and six-phase transmission line protection system were designed in the 4-bus system. Relay setting and external trip logic of the protection system were also calculated and designed. The detailed conclusions of this thesis are listed as below.

In Chapter 2, transmission line parameters and power transfer capability of four cases were studied. The results showed that the impedance and capacitance of six-phase compact transmission line are lower, due to compact tower configuration. The power transfer capability of a six-phase transmission line, with the same phase-to-ground and tower configuration, is the same as three-phase double circuit line. Considering the transformer impedances at both ends of the six-phase transmission line, six-phase transmission line has a lower power transfer capability; especially for a short length transmission line, that transformer impedances are dominated. However, six-phase compact transmission line and six-phase transmission line with a higher voltage level provide more power transfer capability, compared to a three-phase double circuit line. Power transfer capability of six-phase transmission line with higher voltage level, is about 296% of the power transfer capability, provided by the three-phase double circuit line.

In Chapter 3, electric and magnetic field at ground level of four proposed cases were calculated and analyzed. The distributions of electric field at ground level reveal that the maximum electric fields of the six-phase transmission lines are higher than those of a three-phase double circuit transmission line. However, the electric field of six-phase transmission lines decreases faster, compared to the three-phase double circuit line. It should be noted that the ground level electric field of six-phase compact transmission line is significantly lower than that of three-phase double circuit line. This is resulted from a different conductor arrangement, and small phase-to-phase angle. For magnetic field at ground level, the six-phase transmission lines show a dominant advantage, compared to a three-phase double circuit transmission line.

In Chapter 4, right of way requirements for the four proposed cases were calculated. A common right of way for a 138 kV three-phase double circuit line was selected. Based on a selected right of way, ground level electric and magnetic fields of the three-phase double circuit line were calculated at the edge of the right of way. Based on the calculated electric and magnetic field at the edge of the right of way, the six-phase cases were calculated to guarantee the same electric and magnetic fields. Based on these results, it can be concluded that with the same power transfer capability, six-phase lines demand 82% right of way of the three-phase double circuit line at most. With the same right of way, six-phase transmission line can provide about 293% of power transfer capability of the three-phase double circuit line at most.

In Chapter 5, fault analysis of a three-phase double circuit line and a six-phase line were conducted in three systems. Fault locations were selected at different locations on the transmission line. As the results show, six-phase faults have more complicated fault types than that of three-phase double circuit line. Additionally, maximum and minimum ratios of six-phase fault currents are significantly higher compared to that of three-phase double circuit line fault currents. High fault current deviation demands more considerations in six-phase transmission line protection design.

In Chapter 6, based on fault current results from Chapter 5, a three-phase double circuit and a six-phase transmission line protection system were designed in a 4-bus system. Additionally, external trip logic was also designed for both three-phase double circuit and six-phase protection systems to coordinate fault types. It can be concluded that existing protection technology has adequate capability to protect six-phase transmission lines. A six-phase transmission line protection system is more complicated compared to a three-phase double circuit protection system. It should be noted that a current differential relay must be carefully used in six-phase transmission line protection. This is because a low fault current in a six-phase fault may be lower than the maximum load current.

7.2 Future work

Based on the work in this thesis, three potential aspects are worthwhile to explore in the future:

1. Compatibility issues of six-phase lines.

Six phase transmission lines share right of way with other systems, such as optical fiber cables, pipelines, railroad, and wireless communication infrastructure. Does this have any problem with induced voltage and lighting protection?

2. Six-phase transmission line tower design and optimization.

Performance of transmission line electric field, magnetic field, and right of way demand strongly depend on transmission line configuration, especially on the position of conductors. It is difficult to tell whether the existing three-phase double circuit and six-phase tower configurations are the best choices for six-phase transmission lines. More research should be conducted on optimizing towers of six-phase transmission lines.

3. Fault analysis with multiple six-phase transmission lines in a three-phase and six-phase mixed transmission system.

The six-phase fault analysis in this thesis is based on the assumption that only one six-phase transmission line is included in the system. The system containing multiple six-phase transmission lines were not studied. This may be considered as future work.

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APPENDIX A

FAULT CURRENT RESULTS

A.1 4-bus system fault currents

Fault locations were selected at both ends and middle of transmission line. For three-phase double circuit line, three-phase faults were assumed that faults occur at both circuit, and only 1 fault location was considered when a three-phase fault occurred at three-phase double circuit transmission line.

A.1.1 SIX-PHASE FAULTS AT SENDING END OF SIX-PHASE TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	1.4	1.4	1.4	1.4	1.4	1.4	0
ABCDEFN	1.4	1.4	1.4	1.4	1.4	1.4	0
BCDEF	0	1.5	1.6	1.1	1.3	1.5	0
BCDEFN	0	1.3	1.1	1.2	1.5	1.6	1.0
ABCD	1.5	0.9	0.9	1.5	0	0	0
ABCDN	1.0	1.0	1.4	1.8	0	0	2.0
ABDF	1.0	1.2	0	1.7	0	1.3	0
ABDFN	1.2	1.5	0	1.5	0	1.1	1.2
BCEF	0	1.4	1.4	0	1.4	1.4	0
BCEFN	0	1.4	1.4	0	1.4	1.4	0
ABD	1.2	0.9	0	1.6	0	0	0
ABDN	1.0	1.3	0	1.7	0	0	1.3
ABF	0.4	1.2	0	0	0	1.2	0
ABFN	1.2	1.8	0	0	0	1.7	2.9
BDF	0	1.4	0	1.4	0	1.4	0
BDFN	0	1.4	0	1.4	0	1.4	0
AD	1.3	0	0	1.4	0	0	0
ADN	1.3	0	0	1.4	0	0	0
BC	0	0.7	0.7	0	0	0	0
BCN	0	1.1	1.6	0	0	0	2.4
BF	0	1.2	0	0	0	1.2	0
BFN	0	1.2	0	0	0	1.7	1.6
AN	1.4	0	0	0	0	0	1.4

A.1.2 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	1.28	1.28	1.28	1.28	1.28	1.28	0
ABCDEFN	1.28	1.28	1.28	1.28	1.28	1.28	0
BCDEF	0	1.42	1.17	1.02	1.17	1.42	0
BCDEFN	0	1.28	1.16	1.16	1.28	1.4	0.76
ABCD	1.39	0.84	0.84	1.39	0	0	0
ABCDN	1.15	1.01	1.18	1.44	0	0	1.45
ABDF	0.96	1.15	0	1.59	0	1.15	0
ABDFN	1.15	1.29	0	1.41	0	1.14	0.84
BCEF	0	1.28	1.28	0	1.28	1.28	0
BCEFN	0	1.28	1.28	0	1.28	1.28	0
ABD	1.13	0.85	0	1.53	0	0	0
ABDN	1.12	1.15	0	1.43	0	0	0.93
ABF	0.43	1.12	0	0	0	1.12	0
ABFN	1.03	1.36	0	0	0	1.56	1.73
BDF	0	1.28	0	1.28	0	1.28	0
BDFN	0	1.28	0	1.28	0	1.28	0
AD	1.28	0	0	1.28	0	0	0
ADN	1.28	0	0	1.28	0	0	0
BC	0	0.64	0.64	0	0	0	0
BCN	0	0.96	1.22	0	0	0	1.79
BF	0	1.1	0	0	0	1.1	0
BFN	0	1.25	0	0	0	1.46	1.57
AN	1.15	0	0	0	0	0	1.15

A.1.3 SIX-PHASE FAULTS AT RECEIVING END OF SIX-PHASE TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	0.67	0.67	0.67	0.67	0.67	0.67	0
ABCDEFN	0.67	0.67	0.67	0.67	0.67	0.67	0
BCDEF	0	0.75	0.61	0.54	0.61	0.75	0
BCDEFN	0	0.48	0.82	1	0.95	0.68	2.34
ABCD	0.73	0.44	0.44	0.73	0	0	0
ABCDN	0.71	1	1.05	0.84	0	0	2.72
ABDF	0.5	0.6	0	0.84	0	0.6	0
ABDFN	0.89	0.84	0	0.45	0	0.77	1.57
BCEF	0	0.67	0.67	0	0.67	0.67	0
BCEFN	0	0.67	0.67	0	0.67	0.67	0
ABD	0.59	0.45	0	0.81	0	0	0
ABDN	0.75	0.84	0	0.63	0	0	1.18
ABF	0.22	0.59	0	0	0	0.59	0
ABFN	1.01	0.92	0	0	0	0.34	1.53
BDF	0	0.67	0	0.67	0	0.67	0
BDFN	0	0.67	0	0.67	0	0.67	0
AD	0.67	0	0	0.67	0	0	0
ADN	0.67	0	0	0.67	0	0	0
BC	0	0.34	0.34	0	0	0	0
BCN	0	0.87	0.89	0	0	0	1.63
BF	0	0.58	0	0	0	0.58	0
BFN	0	0.6	0	0	0	0.63	0.4
AN	0.78	0	0	0	0	0	0.78

A.1.4 THREE-PHASE FAULTS AT SENDING END OF THREE-PHASE DOUBLE CIRCUIT TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	1.15	1.16	1.16	1.15	1.16	1.16	0
A1B1C1A2B2C2N	1.15	1.16	1.16	1.15	1.16	1.16	0
B1C1A2B2C2	0	1.10	1.12	2.06	1.10	1.12	0
B1C1A2B2C2N	0	1.26	0.56	1.63	1.26	1.16	1.47
A1B1A2C2	1.08	2.02	0	1.08	0	2.01	0
A1B1A2C2N	1.32	1.85	0	1.32	0	1.82	1.24
A1A2B2C2	1.08	2.02	0	1.08	0	2.01	0
A1A2B2C2N	1.32	1.85	0	1.32	0	1.82	1.24
C1C2B1B2	0	1.00	1.00	0	1.00	1.00	0
C1C2B1B2N	0	1.57	1.61	0	1.57	1.61	4.95
A1A2C2	0.91	0	0	0.91	0	1.84	0
A1A2C2N	1.59	0	0	1.59	0	2.44	4.29
A1B2C2	1.96	0	0	0	1.96	1.96	0
A1B2C2N	1.96	0	0	0	1.96	1.96	0
A2B2C2	0	0	0	1.96	1.96	1.96	0
A2B2C2N	0	0	0	1.96	1.95	1.96	0
A1A2	0	0	0	0	0	0	0
A1A2N	1.58	0	0	1.58	0	0	3.16
B1C2	0	1.69	0	0	0	1.68	0
B1C2N	0	2.42	0	0	0	2.50	2.56
B2C2	0	0	0	0	1.69	1.68	0
B2C2N	0	0	0	0	2.42	2.50	2.56
A1N	X	X	X	X	X	X	X

A.1.5 Three-phase faults at middle of three-phase double circuit transmission line

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	0.69	0.69	0.69	0.69	0.69	0.69	0
A1B1C1A2B2C2N	0.69	0.69	0.69	0.69	0.69	0.69	0
B1C1A2B2C2	0	0.66	0.66	1.17	0.66	0.66	0
B1C1A2B2C2N	0	0.69	0.69	1.10	0.69	0.69	0.27
A1B1A2C2	0.64	1.15	0	0.64	0	1.15	0
A1B1A2C2N	0.69	1.10	0	0.69	0	1.10	0.27
A1A2B2C2	0.64	0	0	0.64	1.15	1.15	0
A1A2B2C2N	0.69	0	0	0.69	1.10	1.11	0.27
C1C2B1B2	0	0.60	0.59	0	0.60	0.59	0
C1C2B1B2N	0	0.70	0.66	0	0.70	0.66	1.33
A1A2C2	0.53	0	0	0.53	0	1.06	0
A1A2C2N	0.66	0	0	0.66	0	1.15	1.22
A1B2C2	1.16	0	0	0	1.16	1.16	0
A1B2C2N	1.16	0	0	0	1.16	1.16	0
A2B2C2	0	0	0	1.16	1.16	1.16	0
A2B2C2N	0	0	0	1.16	1.16	1.16	0
A1A2	0	0	0	0	0	0	0
A1A2N	0.68	0	0	0.68	0	0	1.36
B1C2	0	1.00	0	0	0	1.00	0
B1C2N	0	1.18	0	0	0	1.12	1.14
B2C2	0	0	0	0	1.00	1.00	0
B2C2N	0	0	0	0	1.18	1.12	1.14
A1N	X	X	X	X	X	X	X

A.1.6 THREE-PHASE FAULTS AT RECEIVING END OF THREE-PHASE DOUBLE CIRCUIT TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	0.57	0.57	0.57	0.57	0.57	0.57	0
A1B1C1A2B2C2N	0.57	0.57	0.57	0.57	0.57	0.57	0
B1C1A2B2C2	0	0.56	0.52	1.16	0.52	0.52	0
B1C1A2B2C2N	0	0.59	0.59	0.78	0.59	0.59	0.69
A1B1A2C2	0.57	1.13	0	0.57	0	1.13	0
A1B1A2C2N	0.62	0.92	0	0.62	0	0.92	0.59
A1A2B2C2	0.57	0	0	0.57	1.14	1.12	0
A1A2B2C2N	0.62	0	0	0.62	0.92	0.88	0.60
C1C2B1B2	0	0.49	0.49	0	0.49	0.49	0
C1C2B1B2N	0	0.77	0.83	0	0.77	0.83	2.56
A1A2C2	0.49	0	0	0.49	0	0.97	0
A1A2C2N	0.86	0	0	0.86	0	1.57	2.65
A1B2C2	1.13	0	0	0	1.13	1.12	0
A1B2C2N	1.14	0	0	0	1.13	1.12	0
A2B2C2	0	0	0	1.14	1.13	1.12	0
A2B2C2N	0	0	0	1.14	1.13	1.12	0
A1A2	0	0	0	0	0	0	0
A1A2N	0.79	0	0	0.79	0	0	1.58
B1C2	0	0.98	0	0	0	0.97	0
B1C2N	0	1.54	0	0	0	1.68	2.56
B2C2	0	0	0	0	0.98	0.97	0
B2C2N	0	0	0	0	1.54	1.68	2.56
A1N	X	X	X	X	X	X	X

A.2 9-bus system fault currents

Fault locations were selected at both ends and middle of transmission line. For three-phase double circuit line, three-phase faults were assumed that faults occur at both circuit, and only 1 fault location was considered when a three-phase fault occurred at three-phase double circuit transmission line.

A.2.1 SIX-PHASE FAULTS AT SENDING END OF SIX-PHASE TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	1.02	1.02	1.02	1.02	1.02	1.02	0
ABCDEFN	1.02	1.02	1.02	1.02	1.02	1.02	0
BCDEF	0	1.13	0.93	0.81	0.93	1.13	0
BCDEFN	0	2.09	2.96	3.19	2.69	1.7	11.9
ABCD	1.11	0.67	0.67	1.11	0	0	0
ABCDN	1.6	2.17	2.13	1.53	0	0	6.59
ABDF	0.76	0.92	0	1.27	0	0.92	0
ABDFN	1.72	1.47	0	0.33	0	1.52	3.81
BCEF	0	1.02	1.02	0	1.02	1.02	0
BCEFN	0	1.02	1.02	0	1.02	1.02	0
ABD	0.9	0.68	0	1.22	0	0	0
ABDN	1.29	1.43	0	0.87	0	0	2.26
ABF	0.34	0.9	0	0	0	0.9	0
ABFN	1.85	1.59	0	0	0	0.19	3.1
BDF	0	1.02	0	1.02	0	1.02	0
BDFN	0	1.02	0	1.02	0	1.02	0
AD	1.02	0	0	1.02	0	0	0
ADN	1.02	0	0	1.02	0	0	0
BC	0	0.51	0.51	0	0	0	0
BCN	0	1.49	1.48	0	0	0	2.78
BF	0	0.88	0	0	0	0.88	0
BFN	0	0.92	0	0	0	0.9	0.43
AN	1.25	0	0	0	0	0	1.25

A.2.2 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	1.04	1.04	1.04	1.04	1.04	1.04	0
ABCDEFN	1.04	1.04	1.04	1.04	1.04	1.04	0
BCDEF	0	1.16	0.95	0.83	0.95	1.16	0
BCDEFN	0	1.06	1.05	1.03	1.02	1.03	0.99
ABCD	1.14	0.69	0.69	1.13	0	0	0
ABCDN	1.08	1.04	1.01	1.01	0	0	1.74
ABDF	0.78	0.94	0	1.3	0	0.94	0
ABDFN	1.03	1.02	0	1.05	0	1.05	1
BCEF	0	1.04	1.04	0	1.04	1.04	0
BCEFN	0	1.04	1.04	0	1.04	1.04	0
ABD	0.92	0.69	0	1.25	0	0	0
ABDN	1.05	1.03	0	1.03	0	0	1.01
ABF	0.35	0.92	0	0	0	0.92	0
ABFN	1.02	1	0	0	0	1.06	0.9
BDF	0	1.04	0	1.04	0	1.04	0
BDFN	0	1.04	0	1.04	0	1.04	0
AD	1.04	0	0	1.04	0	0	0
ADN	1.04	0	0	1.04	0	0	0
BC	0	0.52	0.52	0	0	0	0
BCN	0	1.05	1.01	0	0	0	1.77
BF	0	0.9	0	0	0	0.9	0
BFN	0	1.06	0	0	0	1.03	1.06
AN	1.03	0	0	0	0	0	1.03

A.2.3 Six-phase faults at receiving end of six-phase transmission line

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	0.9	0.9	0.9	0.9	0.9	0.9	0
ABCDEFN	0.9	0.9	0.9	0.9	0.9	0.9	0
BCDEF	0	1	0.83	0.72	0.83	1.01	0
BCDEFN	0	1.38	1.41	1.08	0.55	0.48	2.9
ABCD	0.98	0.6	0.6	0.98	0	0	0
ABCDN	1.6	1.63	1.23	0.5	0	0	4.17
ABDF	0.68	0.81	0	1.13	0	0.81	0
ABDFN	1.21	0.81	0	0.75	0	1.35	2.41
BCEF	0	0.9	0.9	0	0.9	0.9	0
BCEFN	0	0.9	0.9	0	0.9	0.9	0
ABD	0.8	0.6	0	1.08	0	0	0
ABDN	1.22	1.18	0	0.61	0	0	1.8
ABF	0.3	0.8	0	0	0	0.8	0
ABFN	1.48	1.04	0	0	0	0.56	2.07
BDF	0	0.9	0	0.9	0	0.9	0
BDFN	0	0.9	0	0.9	0	0.9	0
AD	0.9	0	0	0.9	0	0	0
ADN	0.9	0	0	0.9	0	0	0
BC	0	0.45	0.45	0	0	0	0
BCN	0	1.34	1.19	0	0	0	2.38
BF	0	0.78	0	0	0	0.78	0
BFN	0	0.93	0	0	0	0.7	0.51
AN	1.09	0	0	0	0	0	1.09

A.2.4 THREE-PHASE FAULTS AT SENDING END OF THREE-PHASE DOUBLE CIRCUIT TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	1.07	1.07	1.07	1.07	1.07	1.07	0
A1B1C1A2B2C2N	1.07	1.07	1.07	1.07	1.07	1.07	0
B1C1A2B2C2	0	1.07	1.07	2.16	1.07	1.07	0
B1C1A2B2C2N	0	1.07	1.07	2.16	1.07	1.07	0
A1B1A2C2	1.07	2.16	0	1.07	0	2.16	0
A1B1A2C2N	1.07	2.16	0	1.07	0	2.16	0
A1A2B2C2	1.07	2.16	0	1.07	0	2.16	0
A1A2B2C2N	1.07	2.16	0	1.07	0	2.16	0
C1C2B1B2	0	0.93	0.93	0	0.93	0.93	0
C1C2B1B2N	0	0.65	1.21	0	0.65	1.21	3.39
A1A2C2	0.93	0	0	0.93	0	1.87	0
A1A2C2N	0.65	0	0	0.65	0	1.21	3.39
A1B2C2	2.14	0	0	0	2.14	2.14	0
A1B2C2N	2.14	0	0	0	2.14	2.14	0
A2B2C2	0	0	0	2.14	2.14	2.14	0
A2B2C2N	0	0	0	2.14	2.14	2.14	0
A1A2	0	0	0	0	0	0	0
A1A2N	1.32	0	0	1.32	0	0	2.64
B1C2	0	1.87	0	0	0	1.87	0
B1C2N	0	2.61	0	0	0	2.42	3.39
B2C2	0	0	0	0	1.87	1.87	0
B2C2N	0	0	0	0	2.61	2.42	3.39
AN	X	X	X	X	X	X	X

A.2.5 THREE-PHASE FAULTS AT MIDDLE OF THREE-PHASE DOUBLE CIRCUIT TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	1.09	1.09	1.09	1.09	1.09	1.09	0
A1B1C1A2B2C2N	1.09	1.09	1.09	1.09	1.09	1.09	0
B1C1A2B2C2	0	1.09	1.09	2.18	1.09	1.09	0
B1C1A2B2C2N	0	1.09	1.09	2.18	1.09	1.09	0
A1B1A2C2	1.09	2.18	0	1.09	0	2.18	0
A1B1A2C2N	1.09	2.18	0	1.09	0	2.18	0
A1A2B2C2	1.09	2.18	0	1.09	0	2.18	0
A1A2B2C2N	1.09	2.18	0	1.09	0	2.18	0
C1C2B1B2	0	0.95	0.95	0	0.95	0.95	0
C1C2B1B2N	0	0.67	1.23	0	0.67	1.23	3.41
A1A2C2	0.95	0	0	0.95	0	1.89	0
A1A2C2N	0.67	0	0	0.67	0	1.23	3.41
A1B2C2	2.16	0	0	0	2.16	2.16	0
A1B2C2N	2.16	0	0	0	2.16	2.16	0
A2B2C2	0	0	0	2.16	2.16	2.16	0
A2B2C2N	0	0	0	2.16	2.16	2.16	0
A1A2	0	0	0	0	0	0	0
A1A2N	1.34	0	0	1.34	0	0	2.66
B1C2	0	1.89	0	0	0	1.89	0
B1C2N	0	2.63	0	0	0	2.44	3.41
B2C2	0	0	0	0	1.89	1.89	0
B2C2N	0	0	0	0	2.63	2.44	3.41
AN	X	X	X	X	X	X	X

A.2.6 THREE-PHASE FAULTS AT RECEIVING END OF THREE-PHASE DOUBLE CIRCUIT TRANSMISSION LINE

Fault Type	Phase current (kA)						
	A1	B1	C1	A2	B2	C2	N
A1B1C1A2B2C2	0.98	0.98	0.98	0.98	0.98	0.98	0
A1B1C1A2B2C2N	0.98	0.98	0.98	0.98	0.98	0.98	0
B1C1A2B2C2	0	0.98	0.98	1.97	0.98	0.98	0
B1C1A2B2C2N	0	0.98	0.98	1.97	0.98	0.98	0
A1B1A2C2	0.98	1.97	0	0.98	0	1.97	0
A1B1A2C2N	0.98	1.97	0	0.98	0	1.97	0
A1A2B2C2	0.98	1.97	0	0.98	0	1.97	0
A1A2B2C2N	0.98	1.97	0	0.98	0	1.97	0
C1C2B1B2	0	0.85	0.85	0	0.85	0.85	0
C1C2B1B2N	0	0.55	1.23	0	0.55	1.23	3.2
A1A2C2	0.85	0	0	0.85	0	1.70	0
A1A2C2N	1.23	0	0	1.23	0	2.21	3.19
A1B2C2	2.09	0	0	0	2.09	2.09	0
A1B2C2N	2.09	0	0	0	2.09	2.09	0
A2B2C2	0	0	0	2.09	2.09	2.09	0
A2B2C2N	0	0	0	2.09	2.09	2.09	0
A1A2	0	0	0	0	0	0	0
A1A2N	1.22	0	0	1.22	0	0	2.44
B1C2	0	1.71	0	0	0	1.71	0
B1C2N	0	2.21	0	0	0	2.46	3.20
B2C2	0	0	0	0	1.71	1.71	0
B2C2N	0	0	0	0	2.21	2.46	3.20
AN	X	X	X	X	X	X	X

A.3 118-bus system fault currents

In 118-bus system, six transmission lines were upgraded to a six-phase transmission line, respectively. Fault locations were selected at both ends and middle of transmission line.

A.3.1 SIX-PHASE FAULTS AT SENDING END OF SIX-PHASE LINE FROM BUS 8 TO BUS 30

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	7.91	7.91	7.91	7.91	7.91	7.91	0
ABCDEFN	7.91	7.91	7.91	7.91	7.91	7.91	0
BCDEF	0	8.8	7.25	6.32	7.25	8.8	0
BCDEFN	0	9.59	5.27	4.15	8.43	11.6	14.73
ABCD	8.62	5.23	5.23	8.62	0	0	0
ABCDN	10.61	6.96	14.33	20.65	0	0	48.57
ABDF	5.93	7.13	0	9.88	0	7.13	0
ABDFN	6.04	12.75	0	15.05	0	2.34	28.0
BCEF	0	7.91	7.91	0	7.91	7.91	0
BCEFN	0	7.91	7.91	0	7.91	7.91	0
ABD	6.97	5.27	0	9.5	0	0	0
ABDN	9.1	15.9	0	16.7	0	0	36.72
ABF	2.64	6.97	0	0	0	6.97	0
ABFN	26.1	29.6	0	0	0	19.7	73.2
BDF	0	7.91	0	7.91	0	7.91	0
BDFN	0	7.91	0	7.91	0	7.91	0
AD	7.91	0	0	7.91	0	0	0
ADN	7.91	0	0	7.91	0	0	0
BC	0	3.95	3.95	0	0	0	0
BCN	0	15.2	17.2	0	0	0	31.5
BF	0	6.85	0	0	0	6.85	0
BFN	0	4.52	0	0	0	9.3	5.13
AN	11.1	0	0	0	0	0	11.11

A.3.2 Six-phase faults at middle of six-phase transmission line from bus 8 to bus 30

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	7.23	7.23	7.23	7.23	7.23	7.23	0
ABCDEFN	7.23	7.23	7.23	7.23	7.23	7.23	0
BCDEF	0	8.05	6.62	5.78	6.62	8.05	0
BCDEFN	0	6.37	7.82	8.65	8.25	6.89	14.4
ABCD	7.88	4.78	4.78	7.88	0	0	0
ABCDN	7.2	8.95	9.22	7.84	0	0	20.8
ABDF	5.42	6.51	0	9.03	0	6.52	0
ABDFN	8.42	8.05	0	6.04	0	7.74	12.03
BCEF	0	7.23	7.23	0	7.23	7.23	0
BCEFN	0	7.23	7.23	0	7.23	7.23	0
ABD	6.37	4.82	0	8.69	0	0	0
ABDN	7.7	8.26	0	6.9	0	0	10.3
ABF	2.41	6.37	0	0	0	6.37	0
ABFN	9.29	8.66	0	0	0	5.18	12.1
BDF	0	7.23	0	7.23	0	7.23	0
BDFN	0	7.23	0	7.23	0	7.23	0
AD	7.23	0	0	7.23	0	0	0
ADN	7.23	0	0	7.23	0	0	0
BC	0	3.61	3.61	0	0	0	0
BCN	0	8.54	8.7	0	0	0	15.7
BF	0	6.26	0	0	0	6.26	0
BFN	0	6.72	0	0	0	6.92	5.43
AN	8.03	0	0	0	0	0	8.03

A.3.3 Six-phase faults at receiving end of six-phase transmission line from bus 8 to bus 30

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	6.91	6.91	6.91	6.91	6.91	6.91	0
ABCDEFN	6.91	6.91	6.91	6.91	6.91	6.91	0
BCDEF	0	7.7	6.33	5.53	6.34	7.7	0
BCDEFN	0	6.08	5.99	6.91	7.79	7.86	8.32
ABCD	7.53	4.57	4.57	7.53	0	0	0
ABCDN	5.12	6.34	8.06	8.71	0	0	14.42
ABDF	5.18	6.23	0	8.64	0	6.23	0
ABDFN	7.07	7.86	0	6.91	0	6.08	8.32
BCEF	0	6.91	6.91	0	6.91	6.91	0
BCEFN	0	6.91	6.91	0	6.91	6.91	0
ABD	6.1	4.61	0	8.31	0	0	0
ABDN	6.2	7.2	0	7.69	0	0	8.14
ABF	2.3	6.1	0	0	0	6.1	0
ABFN	7.62	8.87	0	0	0	6.76	12.9
BDF	0	6.91	0	6.91	0	6.91	0
BDFN	0	6.91	0	6.91	0	6.91	0
AD	6.91	0	0	6.91	0	0	0
ADN	6.91	0	0	6.91	0	0	0
BC	0	3.46	3.46	0	0	0	0
BCN	0	6.84	8.29	0	0	0	13.53
BF	0	5.99	0	0	0	5.99	0
BFN	0	5.95	0	0	0	7.57	6.49
AN	7.39	0	0	0	0	0	7.39

A.3.4 Six-phase faults at sending end of six-phase transmission line from bus 23 to bus 32

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.91	5.9	5.9	5.9	5.91	5.91	0
ABCDEFN	5.91	5.9	5.9	5.9	5.91	5.91	0
BCDEF	0	6.583	5.41	4.72	5.41	6.58	0
BCDEFN	0	5.15	7.29	8.16	7.31	5.17	17.19
ABCD	6.44	3.91	3.91	6.43	0	0	0
ABCDN	6.5	8.47	8.48	6.56	0	0	21.5
ABDF	4.43	5.32	0	7.38	0	5.32	0
ABDFN	7.54	6.87	0	4.27	0	6.86	12.44
BCEF	0	5.9	5.9	0	5.91	5.91	0
BCEFN	0	5.9	5.9	0	5.91	5.91	0
ABD	5.21	3.94	0	7.1	0	0	0
ABDN	6.63	7.18	0	5.38	0	0	9.74
ABF	1.97	5.21	0	0	0	5.21	0
ABFN	8.46	7.52	0	0	0	3.35	11.81
BDF	0	5.9	0	5.9	0	5.91	0
BDFN	0	5.9	0	5.9	0	5.91	0
AD	5.91	0	0	5.91	0	0	0
ADN	5.91	0	0	5.91	0	0	0
BC	0	2.95	2.95	0	0	0	0
BCN	0	7.54	7.54	0	0	0	13.9
BF	0	5.11	0	0	0	5.11	0
BFN	0	5.45	0	0	0	5.46	3.8
AN	6.8	0	0	0	0	0	6.8

A.3.5 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE FROM BUS 23 TO BUS 32

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.73	5.73	5.73	5.73	5.73	5.73	0
ABCDEFN	5.73	5.73	5.73	5.73	5.73	5.73	0
BCDEF	0	6.38	5.25	4.59	5.25	6.38	0
BCDEFN	0	5.73	5.96	5.97	5.75	5.51	6.93
ABCD	6.25	3.79	3.79	6.25	0	0	0
ABCDN	5.95	6.17	5.99	5.55	0	0	11.5
ABDF	4.3	5.17	0	7.17	0	5.17	0
ABDFN	5.96	5.75	0	5.51	0	5.95	6.66
BCEF	0	5.73	5.73	0	5.73	5.73	0
BCEFN	0	5.73	5.73	0	5.73	5.73	0
ABD	5.06	3.82	0	6.89	0	0	0
ABDN	5.94	5.95	0	5.53	0	0	6.4
ABF	1.91	5.06	0	0	0	5.06	0
ABFN	6.18	5.79	0	0	0	5.3	6.02
BDF	0	5.73	0	5.73	0	5.73	0
BDFN	0	5.73	0	5.73	0	5.73	0
AD	5.73	0	0	5.73	0	0	0
ADN	5.73	0	0	5.73	0	0	0
BC	0	2.87	2.87	0	0	0	0
BCN	0	6.14	5.98	0	0	0	10.68
BF	0	4.97	0	0	0	4.97	0
BFN	0	5.72	0	0	0	5.54	5.31
AN	5.94	0	0	0	0	0	5.94

A.3.6 SIX-PHASE FAULTS AT RECEIVING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 23 TO BUS 32

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.89	5.89	5.89	5.89	5.89	5.89	0
ABCDEFN	5.89	5.89	5.89	5.89	5.89	5.89	0
BCDEF	0	6.56	5.4	4.71	5.4	6.56	0
BCDEFN	0	4.98	7.19	8.17	7.43	5.32	17.31
ABCD	6.42	3.9	3.9	6.42	0	0	0
ABCDN	6.4	8.43	8.54	6.69	0	0	21.6
ABDF	4.42	5.31	0	7.37	0	5.31	0
ABDFN	7.54	6.93	0	4.25	0	6.8	12.48
BCEF	0	5.89	5.89	0	5.89	5.89	0
BCEFN	0	5.89	5.89	0	5.89	5.89	0
ABD	5.2	3.93	0	7.08	0	0	0
ABDN	6.59	7.18	0	5.42	0	0	9.76
ABF	1.96	5.2	0	0	0	5.2	0
ABFN	8.47	7.59	0	0	0	3.32	11.9
BDF	0	5.89	0	5.89	0	5.89	0
BDFN	0	5.89	0	5.89	0	5.89	0
AD	5.89	0	0	5.89	0	0	0
ADN	5.89	0	0	5.89	0	0	0
BC	0	2.95	2.95	0	0	0	0
BCN	0	7.51	7.56	0	0	0	13.9
BF	0	5.1	0	0	0	5.1	0
BFN	0	5.41	0	0	0	5.48	3.78
AN	6.79	0	0	0	0	0	6.79

A.3.7 Six-phase faults at sending end of six-phase transmission line from bus 1 to bus 3

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	3.95	3.95	3.95	3.95	3.95	3.95	0
ABCDEFN	3.95	3.95	3.95	3.95	3.95	3.95	0
BCDEF	0	4.4	3.62	3.16	3.62	4.4	0
BCDEFN	0	3.35	5.55	6.44	5.69	3.57	16.4
ABCD	4.3	2.61	2.61	4.3	0	0	0
ABCDN	4.7	6.35	6.4	4.81	0	0	17.4
ABDF	2.96	3.56	0	4.93	0	3.56	0
ABDFN	5.48	4.92	0	2.42	0	4.86	10.06
BCEF	0	3.95	3.95	0	3.95	3.95	0
BCEFN	0	3.95	3.95	0	3.9	3.95	0
ABD	3.48	2.63	0	4.74		0	0
ABDN	4.58	5.05	0	3.55	0	0	7.25
ABF	1.32	3.48	0	0	0	3.48	0
ABFN	6.15	5.43	0	0	0	1.75	9.29
BDF	0	3.95	0	3.95	0	3.95	0
BDFN	0	3.95	0	3.95	0	3.95	0
AD	3.95	0	0	3.95	0	0	0
ADN	3.95	0	0	3.95	0	0	0
BC	0	1.97	1.97	0	0	0	0
BCN	0	5.28	5.3	0	0	0	9.82
BF	0	3.42	0	0	0	3.42	0
BFN	0	3.58	0	0	0	3.61	2.23
AN	4.66	0	0	0	0	0	4.66

A.3.8 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE FROM BUS 1 TO BUS 3

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	3.65	3.65	3.65	3.65	3.65	3.65	0
ABCDEFN	3.65	3.65	3.65	3.65	3.65	3.65	0
BCDEF	0	4.06	3.35	2.92	3.35	4.07	0
BCDEFN	0	3.3	4.58	5.06	4.47	3.11	10.7
ABCD	3.98	2.41	2.41	3.98	0	0	0
ABCDN	4.1	5.28	5.23	3.99	0	0	13.4
ABDF	2.74	3.29	0	4.56	0	3.29	0
ABDFN	4.67	4.22	0	2.63	0	4.28	7.73
BCEF	0	3.65	3.65	0	3.65	3.65	0
BCEFN	0	3.65	3.65	0	3.65	3.65	0
ABD	3.22	2.43	0	4.39	0	0	0
ABDN	4.13	4.45	0	3.3	0	0	6.04
ABF	1.22	3.22	0	0	0	3.22	0
ABFN	5.24	4.62	0	0	0	2.06	7.26
BDF	0	3.65	0	3.65	0	3.65	0
BDFN	0	3.65	0	3.65	0	3.65	0
AD	3.65	0	0	3.65	0	0	0
ADN	3.65	0	0	3.65	0	0	0
BC	0	1.83	1.83	0	0	0	0
BCN	0	4.68	4.65	0	0	0	8.59
BF	0	3.16	0	0	0	3.16	0
BFN	0	3.39	0	0	0	3.365	2.34
AN	4.21	0	0	0	0	0	4.21

A.3.9 Six-phase faults at receiving end of six-phase transmission line from bus 1 to bus 3

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	3.56	3.56	3.56	3.56	3.56	3.56	0
ABCDEFN	3.56	3.56	3.56	3.56	3.56	3.56	0
BCDEF	0	3.96	3.26	2.85	3.26	3.96	0
BCDEFN	0	3.01	5.04	5.85	5.18	3.24	15.03
ABCD	3.88	2.35	2.35	3.88	0	0	0
ABCDN	4.2	5.75	5.8	4.36	0	0	15.8
ABDF	2.67	3.21	0	4.45	0	3.21	0
ABDFN	4.95	4.45	0	2.16	0	4.39	9.14
BCEF	0	3.56	3.56	0	3.56	3.56	0
BCEFN	0	3.56	3.56	0	3.56	3.56	0
ABD	3.14	2.37	0	4.27	0	0	0
ABDN	4.13	4.56	0	3.2	0	0	6.56
ABF	1.19	3.14	0	0	0	3.14	0
ABFN	5.56	4.91	0	0	0	1.5	8.43
BDF	0	3.56	0	3.56	0	3.56	0
BDFN	0	3.56	0	3.56	0	3.56	0
AD	3.56	0	0	3.56	0	0	0
ADN	3.56	0	0	3.56	0	0	0
BC	0	1.78	1.78	0	0	0	0
BCN	0	4.77	4.79	0	0	0	8.87
BF	0	3.08	0	0	0	3.08	0
BFN	0	3.22	0	0	0	3.25	1.99
AN	4.2	0	0	0	0	0	4.2

A.3.10 SIX-PHASE FAULTS AT SENDING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 10 TO BUS 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	3.67	3.67	3.67	3.67	3.67	3.67	0
ABCDEFN	3.67	3.67	3.67	3.67	3.67	3.67	0
BCDEF	0	4.09	3.36	2.94	3.36	4.09	0
BCDEFN	0	3.14	4.99	5.72	5.05	3.23	13.93
ABCD	4	2.43	2.43	4	0	0	0
ABCDN	4.3	5.75	5.77	4.35	0	0	15.5
ABDF	2.75	3.31	0	4.59	0	3.31	0
ABDFN	4.99	4.49	0	2.35	0	4.46	8.94
BCEF	0	3.67	3.67	0	3.67	3.67	0
BCEFN	0	3.67	3.67	0	3.67	3.67	0
ABD	3.24	2.45	0	4.41	0	0	0
ABDN	4.23	4.64	0	3.3	0	0	6.58
ABF	1.22	3.24	0	0	0	3.24	0
ABFN	5.61	4.95	0	0	0	1.73	8.31
BDF	0	3.67	0	3.67	0	3.67	0
BDFN	0	3.67	0	3.67	0	3.67	0
AD	3.67	0	0	3.67	0	0	0
ADN	3.67	0	0	3.67	0	0	0
BC	0	1.84	1.84	0	0	0	0
BCN	0	4.86	4.87	0	0	0	9.01
BF	0	3.18	0	0	0	3.18	0
BFN	0	3.35	0	0	0	3.36	2.14
AN	4.3	0	0	0	0	0	4.3

A.3.11 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE FROM BUS 10 TO BUS 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	4.04	4.04	4.04	4.04	4.04	4.04	0
ABCDEFN	4.04	4.04	4.04	4.04	4.04	4.04	0
BCDEF	0	4.5	3.7	3.23	3.7	4.5	0
BCDEFN	0	3.51	5.04	5.66	5.05	3.52	12.15
ABCD	4.4	2.67	2.67	4.4	0	0	0
ABCDN	4.5	5.86	5.86	4.51	0	0	15.1
ABDF	3.03	3.64	0	5.05	0	3.64	0
ABDFN	5.19	4.73	0	2.88	0	4.72	8.67
BCEF	0	4.04	4.04	0	4.04	4.04	0
BCEFN	0	4.04	4.04	0	4.04	4.04	0
ABD	3.56	2.69	0	4.85	0	0	0
ABDN	4.55	4.94	0	3.67	0	0	6.73
ABF	1.35	3.56	0	0	0	3.56	0
ABFN	5.84	5.18	0	0	0	2.24	8.2
BDF	0	4.04	0	4.04	0	4.04	0
BDFN	0	4.04	0	4.04	0	4.04	0
AD	4.04	0	0	4.04	0	0	0
ADN	4.04	0	0	4.04	0	0	0
BC	0	2.02	2.02	0	0	0	0
BCN	0	5.18	5.18	0	0	0	9.54
BF	0	3.5	0	0	0	3.5	0
BFN	0	3.72	0	0	0	3.73	2.57
AN	4.66	0	0	0	0	0	4.66

A.3.12 SIX-PHASE FAULTS AT RECEIVING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 10 TO BUS 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	3.67	3.67	3.67	3.67	3.67	3.67	0
ABCDEFN	3.67	3.67	3.67	3.67	3.67	3.67	0
BCDEF	0	4.09	3.36	2.94	3.36	4.09	0
BCDEFN	0	3.14	4.99	5.72	5.05	3.23	13.93
ABCD	4	2.43	2.43	4	0	0	0
ABCDN	4.3	5.75	5.77	4.35	0	0	15.5
ABDF	2.75	3.31	0	4.59	0	3.31	0
ABDFN	4.99	4.49	0	2.35	0	4.46	8.94
BCEF	0	3.67	3.67	0	3.67	3.67	0
BCEFN	0	3.67	3.67	0	3.67	3.67	0
ABD	3.24	2.45	0	4.41	0	0	0
ABDN	4.23	4.64	0	3.3	0	0	6.58
ABF	1.22	3.24	0	0	0	3.24	0
ABFN	5.61	4.95	0	0	0	1.73	8.31
BDF	0	3.67	0	3.67	0	3.67	0
BDFN	0	3.67	0	3.67	0	3.67	0
AD	3.67	0	0	3.67	0	0	0
ADN	3.67	0	0	3.67	0	0	0
BC	0	1.84	1.84	0	0	0	0
BCN	0	4.86	4.87	0	0	0	9.01
BF	0	3.18	0	0	0	3.18	0
BFN	0	3.35	0	0	0	3.36	2.14
AN	4.3	0	0	0	0	0	4.3

A.3.13 Six-phase faults at send end of six-phase transmission line from bus 8 to bus 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	4.59	4.59	4.59	4.59	4.59	4.59	0
ABCDEFN	4.59	4.59	4.59	4.59	4.59	4.59	0
BCDEF	0	5.11	4.2	3.67	4.2	5.11	0
BCDEFN	0	3.94	6.04	6.87	6.08	4.01	16
ABCD	5	3.03	3.03	5	0	0	0
ABCDN	5.3	6.99	7.01	5.31	0	0	18.5
ABDF	3.44	4.13	0	5.73	0	4.13	0
ABDFN	6.11	5.52	0	3.06	0	5.5	10.68
BCEF	0	4.59	4.59	0	4.59	4.59	0
BCEFN	0	4.59	4.59	0	4.59	4.59	0
ABD	4.04	3.06	0	5.51	0	0	0
ABDN	5.25	5.73	0	4.14	0	0	8.02
ABF	1.53	4.04	0	0	0	4.04	0
ABFN	6.87	6.07	0	0	0	2.3	10
BDF	0	4.59	0	4.59	0	4.59	0
BDFN	0	4.59	0	4.59	0	4.59	0
AD	4.59	0	0	4.59	0	0	0
ADN	4.59	0	0	4.59	0	0	0
BC	0	2.29	2.29	0	0	0	0
BCN	0	6.01	6.02	0	0	0	11.1
BF	0	3.97	0	0	0	3.97	0
BFN	0	4.2	0	0	0	4.21	2.75
AN	5.35	0	0	0	0	0	5.35

A.3.14 SIX-PHASE FAULTS AT MIDDLE OF SIX-PHASE TRANSMISSION LINE FROM BUS 8 TO BUS 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.11	5.11	5.11	5.11	5.11	5.11	0
ABCDEFN	5.11	5.11	5.11	5.11	5.11	5.11	0
BCDEF	0	5.69	4.68	4.09	4.68	5.69	0
BCDEFN	0	4.51	6.18	6.86	6.16	4.49	13.84
ABCD	5.57	3.38	3.38	5.57	0	0	0
ABCDN	5.6	7.15	7.15	5.57	0	0	17.9
ABDF	3.83	4.6	0	6.39	0	4.61	0
ABDFN	6.41	5.86	0	3.81	0	5.87	10.32
BCEF	0	5.11	5.11	0	5.11	5.11	0
BCEFN	0	5.11	5.11	0	5.11	5.11	0
ABD	4.51	3.41	0	6.14	0	0	0
ABDN	5.7	6.15	0	4.67	0	0	8.22
ABF	1.7	4.51	0	0	0	4.51	0
ABFN	7.18	6.4	0	0	0	3.03	9.82
BDF	0	5.11	0	5.11	0	5.11	0
BDFN	0	5.11	0	5.11	0	5.11	0
AD	5.11	0	0	5.11	0	0	0
ADN	5.11	0	0	5.11	0	0	0
BC	0	2.55	2.55	0	0	0	0
BCN	0	6.45	6.44	0	0	0	11.8
BF	0	4.42	0	0	0	4.42	0
BFN	0	4.74	0	0	0	4.73	3.38
AN	5.85	0	0	0	0	0	5.85

A.3.15 SIX-PHASE FAULTS AT RECEIVING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 8 TO BUS 9

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.45	5.44	5.45	5.45	5.45	5.45	0
ABCDEFN	5.45	5.44	5.45	5.45	5.45	5.45	0
BCDEF	0	6.06	4.99	4.36	4.99	6.06	0
BCDEFN	0	4.66	7.01	7.96	7.09	4.78	18.04
ABCD	5.93	3.6	3.6	5.93	0	0	0
ABCDN	6.2	8.15	8.18	6.25	0	0	21.4
ABDF	4.08	4.91	0	6.81	0	4.91	0
ABDFN	7.17	6.5	0	3.72	0	6.46	12.34
BCEF	0	5.44	5.45	0	5.45	5.45	0
BCEFN	0	5.44	5.45	0	5.45	5.45	0
ABD	4.8	3.63	0	6.54	0	0	0
ABDN	6.19	6.75	0	4.94	0	0	9.37
ABF	1.82	4.8	0	0	0	4.8	0
ABFN	8.06	7.15	0	0	0	2.83	11.6
BDF	0	5.44	0	5.45	0	5.45	0
BDFN	0	5.44	0	5.45	0	5.45	0
AD	5.45	0	0	5.45	0	0	0
ADN	5.45	0	0	5.45	0	0	0
BC	0	2.72	2.72	0	0	0	0
BCN	0	7.08	7.09	0	0	0	13.1
BF	0	4.72	0	0	0	4.72	0
BFN	0	4.99	0	0	0	5.01	3.33
AN	6.33	0	0	0	0	0	6.33

A.3.16 SIX-PHASE FAULTS AT SENDING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 5 TO BUS 6

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	6.67	6.67	6.67	6.67	6.67	6.67	0
ABCDEFN	6.67	6.67	6.67	6.67	6.67	6.67	0
BCDEF	0	7.42	6.11	5.33	6.11	7.43	0
BCDEFN	0	5.67	8.64	9.86	8.79	5.89	22.62
ABCD	7.27	4.41	4.41	7.27	0	0	0
ABCDN	7.6	10.1	10.1	7.72	0	0	26.5
ABDF	5	6.01	0	8.34	0	6.01	0
ABDFN	8.83	8.01	0	4.51	0	7.93	15.3
BCEF	0	6.67	6.67	0	6.67	6.67	0
BCEFN	0	6.67	6.67	0	6.67	6.67	0
ABD	5.88	4.45	0	8.01	0	0	0
ABDN	7.59	8.3	0	6.05	0	0	11.6
ABF	2.22	5.88	0	0	0	5.88	0
ABFN	9.93	8.8	0	0	0	3.41	14.4
BDF	0	6.67	0	6.67	0	6.67	0
BDFN	0	6.67	0	6.67	0	6.67	0
AD	6.67	0	0	6.67	0	0	0
ADN	6.67	0	0	6.67	0	0	0
BC	0	3.33	3.33	0	0	0	0
BCN	0	8.7	8.72	0	0	0	16.1
BF	0	5.77	0	0	0	5.77	0
BFN	0	6.1	0	0	0	6.14	4.05
AN	7.54	0	0	0	0	0	7.54

A.3.17 Six-phase faults at middle of six-phase transmission line from bus 5 to bus 6

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	6.32	6.32	6.32	6.32	6.32	6.32	0
ABCDEFN	6.32	6.32	6.32	6.32	6.32	6.32	0
BCDEF	0	7.04	5.8	5.06	5.8	7.04	0
BCDEFN	0	5.95	7.13	7.54	6.89	5.67	12.4
ABCD	6.89	4.18	4.18	6.89	0	0	0
ABCDN	6.7	7.98	7.83	6.39	0	0	18.0
ABDF	4.74	5.7	0	7.9	0	5.7	0
ABDFN	7.34	6.81	0	5.31	0	6.97	10.41
BCEF	0	6.32	6.32	0	6.32	6.32	0
BCEFN	0	6.32	6.32	0	6.32	6.32	0
ABD	5.58	4.22	0	7.6	0	0	0
ABDN	6.87	7.2	0	5.86	0	0	8.96
ABF	2.11	5.58	0	0	0	5.58	0
ABFN	8.08	7.25	0	0	0	4.57	9.81
BDF	0	6.32	0	6.32	0	6.32	0
BDFN	0	6.32	0	6.32	0	6.32	0
AD	6.32	0	0	6.32	0	0	0
ADN	6.32	0	0	6.32	0	0	0
BC	0	3.16	3.16	0	0	0	0
BCN	0	7.56	7.47	0	0	0	13.6
BF	0	5.48	0	0	0	5.48	0
BFN	0	6.03	0	0	0	5.92	4.78
AN	7.01	0	0	0	0	0	7.01

A.3.18 SIX-PHASE FAULTS AT RECEIVING END OF SIX-PHASE TRANSMISSION LINE FROM BUS 5 TO BUS 6

Fault Type	Phase current (kA)						
	A	B	C	D	E	F	N
ABCDEF	5.79	5.79	5.79	5.79	5.79	5.79	0
ABCDEFN	5.79	5.79	5.79	5.79	5.79	5.79	0
BCDEF	0	6.45	5.31	4.64	5.31	6.45	0
BCDEFN	0	4.9	7.61	8.72	7.77	5.14	20.44
ABCD	6.31	3.83	3.83	6.31	0	0	0
ABCDN	6.6	8.85	8.9	6.78	0	0	23.5
ABDF	4.35	5.22	0	7.24	0	5.22	0
ABDFN	7.74	7.01	0	3.85	0	6.94	13.58
BCEF	0	5.79	5.79	0	5.79	5.79	0
BCEFN	0	5.79	5.79	0	5.79	5.79	0
ABD	5.11	3.86	0	6.96	0	0	0
ABDN	6.62	7.25	0	5.25	0	0	10.2
ABF	1.93	5.11	0	0	0	5.11	0
ABFN	8.71	7.72	0	0	0	2.88	12.7
BDF	0	5.79	0	5.79	0	5.79	0
BDFN	0	5.79	0	5.79	0	5.79	0
AD	5.79	0	0	5.79	0	0	0
ADN	5.79	0	0	5.79	0	0	0
BC	0	2.9	2.9	0	0	0	0
BCN	0	7.6	7.62	0	0	0	14.1
BF	0	5.02	0	0	0	5.02	0
BFN	0	5.29	0	0	0	5.33	3.47
AN	6.76	0	0	0	0	0	6.76