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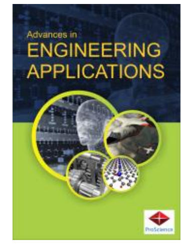

A NARRATIVE APPROACH TO FIVE PHASE TRANSMISSION SYSTEM

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Abstract

The power demand is increasing day to day and is becoming prime requirement. High Phase Order (HPO) transmission system is being considered a viable alternative to meet the demand by increasing the power transmission capability. Mainly the research of HPO systems is going on six and twelve phase transmission systems since they are multiples of three. But there is no difference in magnitude between the line voltage and phase voltage. This paper takes the instigation regarding Five Phase transmission system and results are compared with 132 kV three phase system. This paper investigates the weight of the conductor, sag of the conductor and spacing between the conductors, Inductance and capacitance calculations required in 132 kV Five Phase transmission system. Also, shows the line model of Five Phase transmission system. So, industrial loads can be driven with Five Phase supply as a ripple free torque and efficiency will be increased effectively.

Key words: *High Phase Order systems, Five Phase, Inductance and Capacitance of Five Phase Transmission Line*.

1.0 Introduction

Multiphase (more than three phase) systems are the focus of research recently due to their inherent advantages compared to their conventional systems. The increased interest in HPO Electric Power Transmission over past thirty years can be traced on a CIRGE paper published by L. D. Barthold and H. C. Barnes [1]. Since that time, the thought of HPO transmission has been described in the literature in several papers and report [2-7].

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Among the HPO, six-phase transmission appears to be the most promising solution to the need to increase the capability of existing transmission lines. But with Increase in number of phases certainly enhances the complexity of the system. There are no designs regarding odd phases like 3, 7 etc. as far as researchers know. Recently Five-Phase Induction Motor Drive System [8] is proposed due to several advantages over three-phase machines such as lower pulsations in torque, higher density in torque, fault tolerance, stability and lower current ripple. Already three phase to n (odd) phase transformer connections are proposed [9]. 5-leg inverter is also proposed for

Five Phase supply [10-11]. So in future Five Phase supply may preferred for industrial loads. The present work is investigated on Five Phase transmission system. In this paper Weight of the conductor, sag and spacing, Inductance and Capacitance calculations for Five Phase transmission system are demonstrated.

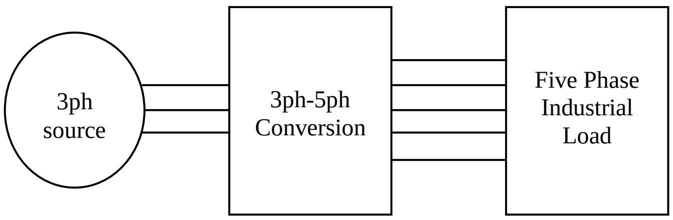

Fig 1 Proposed Scheme Block Diagram

2.0 Five phase supply

Figure 2 shows the Phasor diagram of Five Phase supply. Each phase is displayed by 72° as shown. If $V_{AN} = V_{BN} = V_{CN} = V_{DN} = V_{EN} = V_{Ph}$ (in magnitude) then $V_{AN} = V_{AN} \angle 0^o$, $V_{BN} = V_{BN} \angle{-72^o}$, $V_{CN} = V_{CN} \angle{-144^o}$, $V_{DN} = V_{DN} \angle{-216^o}$ and $V_{EN} = V_{EN} \angle{-288^o}$.

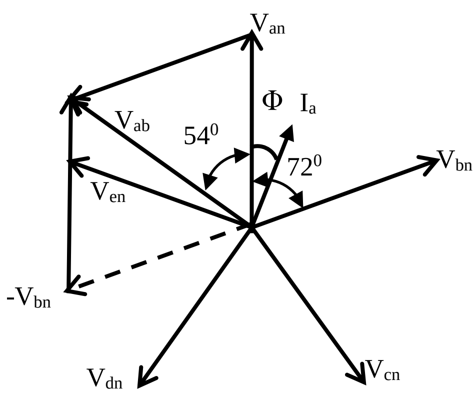

Fig 2 Phasor diagram of Five Phase supply

If V_{AN} is chosen as reference there will be four types of voltage relationships: Lines are displayed by 72° (V_{AB}, V_{BC} etc...), Lines are displayed by 144° (V_{AC}, V_{BD} etc...), Lines are displayed by 216° (V_{AD}, V_{BE} etc...) and Lines are displayed by 288° (V_{AE}). The Voltage relationships are as follows:

$$V_{AB} = V_{Ph}\, 1.175 \angle 54^o \quad (1)$$

$$V_{AC} = V_{Ph}\, 1.902 \angle 18^o \quad (2)$$

$$V_{AD} = V_{Ph}\, 1.902 \angle{-18^o} \quad (3)$$

$$V_{AE} = V_{Ph}\, 1.175 \angle{-54^o} \quad (4)$$

Adding all those voltage relationships results as: ($V_{AN} = V_{Ph}$)

$$V_{AB}+V_{AC}+V_{AD}+V_{AE} = 5\, V_{AN}, \quad (5)$$

The above equation is useful in capacitance to neutral calculation for Five Phase line. Five-Phase Voltage relation: $V_L = 1.175\, V_{Ph}$ and Five-Phase Power (in the case of balanced system):

$$P = 4.25\, V_L I_L \cos Ø. \quad (6)$$

3.0 Sag and Spacing in Five phase transmission line

The main factor effecting inductance and capacitance in transmission line is spacing between conductors. Spacing between conductors depends upon sag. Sag depends upon weight of the conductor. So, in order to compute inductance and capacitance of Five Phase transmission line it has to recognize the weight of the conductor, sag of the conductor and spacing between conductors. Taking into consideration 5 phase- 5 wire system, weight of the conductor can be calculated as follows:

Line current
$$I_L = \frac{P}{4.25 V_L \cos\phi} \quad (7)$$

Power Loss
$$P_L = 5 I_L^{\,2} R \quad (8)$$

$$P_L = \frac{5P^2 \times \rho \times l}{18.0625 \times V_L^2 \cos^2\phi \times a} \quad (9)$$

From above equation it can solve for area of cross-section and hence weight of the aluminium conductor will be:

$$W_{AL} = Volume \times D$$
$$W_{AL} = 5al \times D$$
$$W_{AL} = \frac{1.384 P \times \rho \times l^2}{V_L^2 \cos^2\phi \times (1-\eta)} \times D$$

where, P is power to be transmitted; l is length of the conductor; D is specific gravity of aluminium; ρ is resistivity of aluminium; V_L is line voltage; η is efficiency.

If resistivity and specific gravity of steel instead of aluminium were placed in equation (10) then it will get the weight of steel conductor. Generally for 132kv transmission line *panther* ACSR conductor is used which has 30 aluminium strands and 7 steel strands (Central steel wire with one strand, 1st steel layer with 6 strands, 1st aluminium layer with 12 strands and 2nd aluminium layer with 18 strands). Hence, *panther* conductor has 81.1% of aluminium and 18.9% of steel. The detail weight calculations of *panther* ACSR conductor in Five Phase are presented in results section.

Sag can be calculated by using the formula

$$S = W_r L^2 / 8T \quad (11)$$

where, W_r is Resultant weight per meter length (considering weight of the conductor and wind pressure); L is Span length and T is working tension.

The Spacing of conductors is determined by considerations partly electrical and partly mechanical. Larger spacing causes increase in inductance of the line and hence the voltage drop, so that to keep the latter within a reasonable value the conductors should be as close together as is consistent with prevention of corona. The basic consideration regarding the minimum spacing between conductors is that the electrical clearances between conductors under the worst condition i.e. maximum temperature and wind weight shall not be less than the limits for safety, particularly at the middle of the spans [17]. Empirical formulae commonly employed for determination of Spacing of conductors for an aluminium conductor line is given as:

$$Spacing = \sqrt{S} + \frac{V}{150} \qquad (12)$$

where, S is sag in meters and V is line voltage in kV.

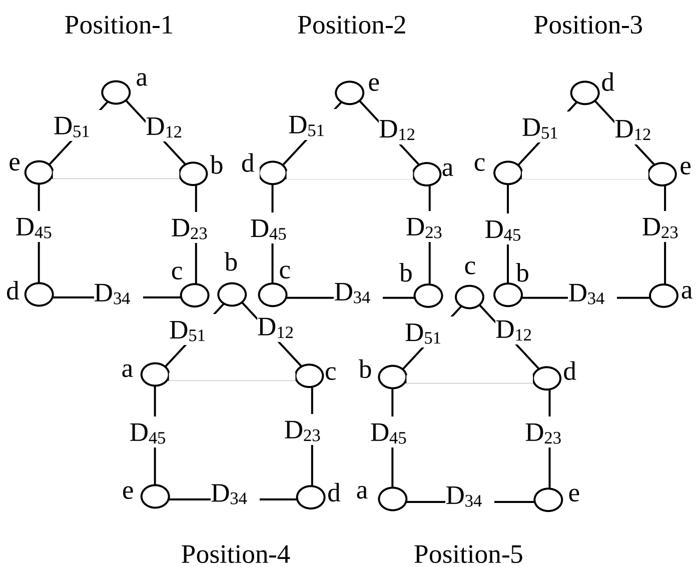

Fig. 3 Fully Transposed Cycle of Five Phase Line

4.0 Inductance of Five Phase Transmission Line

The inductance of a transmission line is calculated as flux linkages per ampere. So far it is considered only single phase and three phase lines. The basic equations for Five Phase lines are also be easily developed. Assuming all conductors with unsymmetrical spacing, the fully transposed cycle is shown in figure 3. For a 5 phase 5 wire line there will no neutral wire, so that $I_a + I_b + I_c + I_d + I_e = 0$. To find the average inductance of one conductor of a transposed line, first determine the flux linkages of a conductor for each position it occupies in the transposition cycle and then determine the average flux linkages. Flux linkages for various positions shown in figure 3 are as follows:

For the 1st position:

$$\lambda_{a1} = 2*10^{-7}\left[I_a \ln\frac{1}{r_a^1} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{23}} + I_d \ln\frac{1}{D_{34}} + I_e \ln\frac{1}{D_{45}}\right] \qquad (13)$$

For the 2nd position:

$$\lambda_{a2} = 2*10^{-7}\left[I_a \ln\frac{1}{r_a^1} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{D_{34}} + I_d \ln\frac{1}{D_{45}} + I_e \ln\frac{1}{D_{51}}\right] \qquad (14)$$

For the 3rd position:

$$\lambda_{a3} = 2*10^{-7}\left[I_a \ln\frac{1}{r_a^1} + I_b \ln\frac{1}{D_{34}} + I_c \ln\frac{1}{D_{45}} + I_d \ln\frac{1}{D_{51}} + I_e \ln\frac{1}{D_{12}}\right] \qquad (15)$$

For the 4th position:

$$\lambda_{a4} = 2*10^{-7}\left[I_a \ln\frac{1}{r_a^1} + I_b \ln\frac{1}{D_{45}} + I_c \ln\frac{1}{D_{51}} + I_d \ln\frac{1}{D_{12}} + I_e \ln\frac{1}{D_{23}}\right] \qquad (16)$$

For the 5th position:

$$\lambda_{a5} = 2*10^{-7}\left[I_a \ln\frac{1}{r_a^1} + I_b \ln\frac{1}{D_{51}} + I_c \ln\frac{1}{D_{12}} + I_d \ln\frac{1}{D_{23}} + I_e \ln\frac{1}{D_{34}}\right] \qquad (17)$$

Average flux linkages of conductor 'a' are:

$$\lambda_a = \frac{\lambda_{a1} + \lambda_{a2} + \lambda_{a3} + \lambda_{a4} + \lambda_{a5}}{5} \qquad (18)$$

But $I_b + I_c + I_d + I_e = -I_a$

$$\lambda_a = 2*10^{-7} I_a \ln\frac{(D_{12}D_{23}D_{34}D_{45}D_{51})^{1/5}}{r_a^1} \qquad (19)$$

The average inductance per phase is:

$$L_a = 2*10^{-7} \ln\frac{(D_{12}D_{23}D_{34}D_{45}D_{51})^{1/5}}{r_a^1} \text{ H/m} \qquad (20)$$

For equilateral spacing, the inductance of Five Phase transmission line will be same as the inductance of three phase transmission line. But for unsymmetrical spacing the inductance of Five Phase line will be lesser than the inductance of three phase line.

5.0 Capacitance of Five phase transmission line

To find the capacitance to neutral of a transposed line, first determine the Voltage drop between two conductors (say a and b). The potential difference between a and b for various positions (Fig 3) are as follows:

For the 1st position:

$$V_{ab1} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{12}}{r} + q_b \ln\frac{r}{D_{12}} + q_c \ln\frac{D_{23}}{D_{13}} + q_d \ln\frac{D_{24}}{D_{14}} + q_e \ln\frac{D_{25}}{D_{15}}\right] \qquad (21)$$

For the 2nd position:

$$V_{ab2} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{23}}{r} + q_b \ln\frac{r}{D_{23}} + q_c \ln\frac{D_{34}}{D_{24}} + q_d \ln\frac{D_{35}}{D_{25}} + q_e \ln\frac{D_{31}}{D_{21}}\right] \qquad (22)$$

For the 3rd position:

$$V_{ab3} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{34}}{r} + q_b \ln\frac{r}{D_{34}} + q_c \ln\frac{D_{45}}{D_{35}} + q_d \ln\frac{D_{41}}{D_{31}} + q_e \ln\frac{D_{42}}{D_{32}} \right] \tag{23}$$

For the 4th position:

$$V_{ab4} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{45}}{r} + q_b \ln\frac{r}{D_{45}} + q_c \ln\frac{D_{51}}{D_{41}} + q_d \ln\frac{D_{52}}{D_{42}} + q_e \ln\frac{D_{53}}{D_{43}} \right] \tag{24}$$

For the 5th position:

$$V_{ab5} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{51}}{r} + q_b \ln\frac{r}{D_{51}} + q_c \ln\frac{D_{12}}{D_{52}} + q_d \ln\frac{D_{13}}{D_{53}} + q_e \ln\frac{D_{14}}{D_{54}} \right] \tag{25}$$

The average of all five voltages is:

$$V_{ab} = \frac{V_{ab1} + V_{ab2} + V_{ab3} + V_{ab4} + V_{ab5}}{5} \tag{26}$$

$$V_{ab} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_b \ln\frac{r}{D_{eq}} \right] \tag{27}$$

Similarly,

$$V_{ac} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_c \ln\frac{r}{D_{eq}} \right] \tag{28}$$

$$V_{ad} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_d \ln\frac{r}{D_{eq}} \right] \tag{29}$$

$$V_{ae} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_e \ln\frac{r}{D_{eq}} \right] \tag{30}$$

Where, $D_{eq} = (D_{12}D_{23}D_{34}D_{45}D_{51})^{1/5}$ (31)

$q_a + q_b + q_c + q_d + q_e = 0$

Adding equations (27) to (30) results in:

$$V_{ab} + V_{ac} + V_{ad} + V_{ae} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} - q_a \ln\frac{r}{D_{eq}} \right] \tag{32}$$

Equating equations (5) and (32), we get:

$$V_{an} = \frac{1}{2\pi k}\left[q_a \ln\frac{(D_{12}D_{23}D_{34}D_{45}D_{51})^{1/5}}{r} \right] \tag{33}$$

So, the capacitance to neutral will be (for air medium K_r=1):

$$C_n = \frac{0.0242}{\ln\dfrac{(D_{12}D_{23}D_{34}D_{45}D_{51})^{1/5}}{r}} \tag{34}$$

Mathematically there is no difference in the formulae of capacitance to neutral for both three phase and Five Phase, only D_{eq} will get differ. So as phase increases the capacitance to neutral increases, capacitive reactance will reduce and charging current will increases. Hence for the Five Phase long transmission lines, the tower height will be increased. But the weight of aluminium conductor and sag in Five Phase lines get decreased. Spacing between conductors is also reduced in Five Phase lines when compared to three phase lines.

6.0 Results and Discussion

Here all the parameters are calculated in two cases: 1) Conductor spacing used in three phase lines is also used in Five Phase lines. 2) Spacing is separately calculated for Five Phase lines. MATLAB editor is used for calculation of all parameters.

A. Same Spacing is used in Five Phase

For 132kV three phase transmission line, weight of the conductor, sag of the conductor and spacing between the conductors are calculated by using following parameters:

Table. 1 Parameters used in three phase transmission lines

Parameter	Value
Power to be transmitted (MW)	30
Frequency (Hz)	50
Line voltage (kV)	132
Length of line (km)	120
Resistivity of aluminum (ohm-meter)	$2.6*10^{-8}$
Specific gravity of aluminum (Kg/m^3)	2000
Power factor	0.9
Efficiency (%)	90
Span length	300
Ultimate strength	3000
Safety factor	2
Diameter of conductor	1cm
Wind pressure (Kg/m^2)	29.2

The results are obtained by using MATLAB Program which is shown in appendix and results are tabulated in Table. 2

Table. 2 Results obtained from the MATLAB editor for three phase transmission lines.

Parameters	Value
Weight of ACSR conductor (Kg / 120 km)	120229.25
Weight of ACSR conductor (Kg per km)	1001.910
Weight of ACSR conductor (Kg per meter)	1.002
Maximum sag in meter	7.826
Spacing Between Conductors in meter	3.677
Sag in meter by neglecting wind pressure	7.514
Spacing Between Conductors in meter by neglecting wind pressure	3.621
Inductance in mH per km	1.399
Inductive Reactance in mohm per km	438.799
Capacitance to neutral in µF per km	0.003594
Capacitive Reactance in Mohm per km	0.885705
Charging Current in Ampere per km	0.086045
Inductance in mH per 120 km	167.60912
Inductive Reactance in mohm per 120 km	52655.959
Capacitance to neutral in µF per 120 km	0.43126
Capacitive Reactance in Mohm per 120 km	106.2846
Charging Current in Ampere per 120 km	10.325365

With the same spacing of three phase transmission system which are tabulated in table 2, the results are obtained for Five Phase transmission system and tabulated in Table. 3.

Table. 3 Inductance and capacitance of five phase transmission system for same spacing.

Parameter	Value
Inductance in mH per 120 km	167.6046
Inductive Reactance in mohm per 120 km	52654.584
Capacitance to neutral in µF per 120 km	0.432
Capacitive Reactance in Mohm per 120 km	106.284
Charging Current in Ampere per 120 km	15.216

From Table. 2 and Table. 3 it is conclude that without changing the spacing between conductors the inductive reactance is reduced by small extent. Capacitance effect is very less when same spacing is assumed. But the effect of charging current is more in case of Five Phase system.

B. Spacing between conductors in Five Phase transmission line is Separately calculated

For calculating spacing between the lines in Five Phase Transmission system the parameter which are in table 1 are used. A program is written in MATLAB using equations (7) to (34) and results are tabulated in Table. 4.

Table. 4 Results for five phase lines

Parameters	Value
Weight of aluminum Kg per 120 km	55465.7596
Weight of aluminum Kg per km	462.214
Weight of aluminum Kg per meter	0.462215
Maximum sag in Five Phase in meter	4.1004
Spacing Between Conductors in meter	2.9049
Sag in meter by neglecting wind pressure	3.4666
Spacing between Conductors in meter by neglecting wind pressure	2.74188
Inductance in mH per km	1.3492
Inductive Reactance in mohm per km	423.886
Capacitance to neutral in uF per km	0.003725
Capacitive Reactance in Mohm per km	0.85448
Charging Current in Ampere per km	0.13147
Inductance in mH per 120 km	161.9125
Inductive Reactance in mohm per 120 km	50866.3417
Capacitance to neutral in uF per 120 km	0.44702
Capacitive Reactance in Mohm per 120 km	102.5382
Charging Current in Ampere per 120 km	15.7765

By comparing Table. 2 and Table. 4 it is conclude that the weight of conductor is significantly decreased to 55465.7596 Kg per 120 km from 120229.248 per 120 km, maximum sag is decreased to 4.1 m from 7.8m and spacing between conductors is decreased to 2.9m from 3.6m. Inductive reactance is also reduced by 1789.618 mH per 120 km. But charging current is increased by 5.4515 Ampere per 120 km. For very long transmission lines the effect of charging current will be more then, the tower height has to be increased.

C. Line Model of Five Phase

To calculate sending-end voltage, sending-end current and sending-end power, sending-end power factor in Five Phase transmission line, by considered the approximate exact equation method.

From above tabulated results the series impedance and the shunt admittance for five phase transmission system are:
Series impedance = 75+j*127.165 ohm/300km.
Shunt admittance = 3.9e-9 mho/300km.
The series impedance and the shunt admittance for three phase transmission system are:
Series impedance = 75+j*131.7 ohm/300km.
Shunt admittance = 3.76e-9 mho/300km.

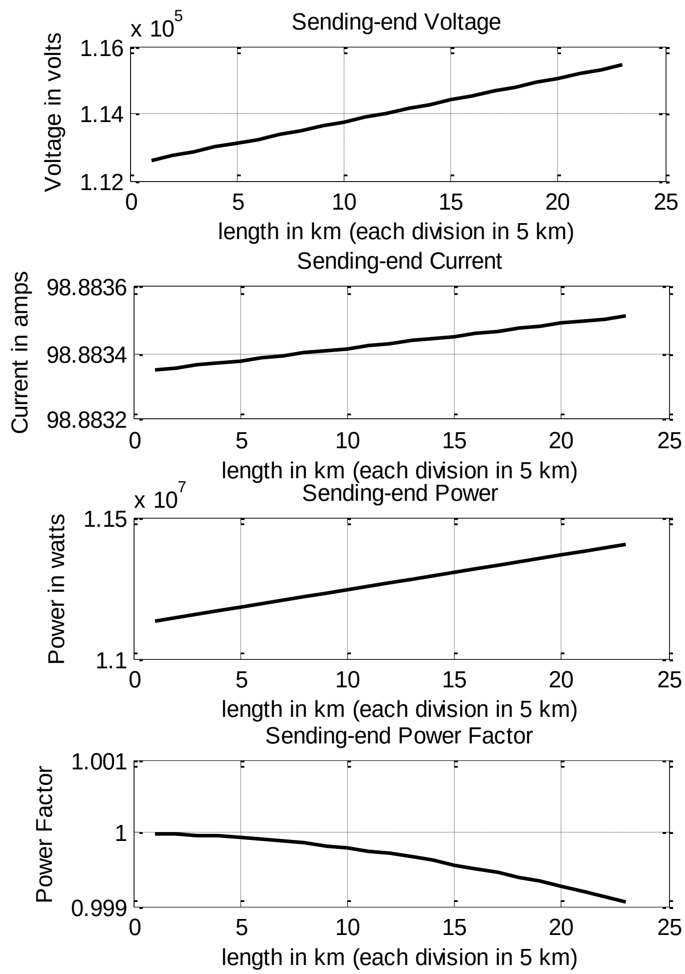

Fig. 4 (a) Sending-end power factor with respect to line length (b) Sending-end voltage with respect to line length (c) Sending-end current with respect to line length (d) Sending-end power with respect to line length.

Program is written in MATLAB which is in appendix. The results are shown in fig. 4. From those characteristics it concludes that Five Phase supply can be proffered for industrial loads.

7.0 Conclusions

This paper proposes a basic concept about Five-Phase Transmission system. It shows the relation between line voltage and phase voltage as well as current and power relations. Spacing between conductors in Five Phase is also determined. Complete calculations of line parameters in Five Phase are done. Here, compiled the line model in Five Phase system. In future the research has to be concentrated on fault analysis and protection of Five Phase system.

APPENDIX

A. ***Program for finding weight, seg, spacing, inductance and capacitance:***

```
T=US/S;
Ww=WP*D;
n=eff/100;
l=len*1000;
Wal=(1.384*p*l*l*P*d)/((1-n)*Vl*Vl*pf*pf);
Ws=(1.384*p1*l*l*P*d1)/((1-n)*Vl*Vl*pf*pf);
Wacsr=(0.810811*Wal)+(0.189189*Ws);
Wacsr1=Wacsr/len;
Wacsr2=Wacsr/(len*1000);
Wr=sqrt((Wacsr2^2)+(Ww^2));
Sag=(Wr*L*L)/(8*T);
Sag1=(Wacsr2*L*L)/(8*T);
Spacing=(sqrt(Sag))+(Vl/150000);
Spacing1=(sqrt(Sag1))+(Vl/150000);
D12=Spacing;
D23=Spacing;
D45=Spacing;
D51=Spacing;
D34=((Spacing+Spacing)-0.2);
r=(D/2)*100;
Vn=Vl/1.175;
GMR=0.7788*r;
GMD=(D12*D23*D45*D51*D34)^(1/5);
GMD1=(GMD*100);
Ind=0.2*(log(GMD1/GMR));
Cap=0.0242/(log(GMD1/r));
Xn=1/(2*pi*f*Cap);
Xl=2*pi*f*Ind;
Ic=Vn/(Xn*1000000);
Ind1=Ind*len;
Cap1=Cap*len;
Xn1=Xn*len;
Xl1=Xl*len;
Ic1=Ic*len;
```

In the above program: US is ultimate strength, S is safety factor, WP is wind pressure, D is diameter of conductor, n=efficiency, Wal is weight of aluminum, Ws is weight of steel conductor, Wacsr is weight of acsr conductor, Ind is inductance, Cap is Capacitance to neutral, len is length of the transmission line, Xl is inductive reactance, Xn is capacitive reactance and Ic is charging current.

B. ***Program for finding sending – end voltage, sending – end current and sending – end power factor in Five Phase:***

```
IR = PR/(VR*pfload);
z = Z/l;
y = Y/l;
i = 1;
for l = 10:5:120,
   A = 1+(y*l)*(z*l)/2
   B = (z*l)*(1+(y*l)*(z*l)/6)
   C = (y*l)*(1+(y*l)*(z*l)/6)
   D = A
   Vs_approx(i) = A*VR+B*IR
   Is_approx(i) = C*VR+D*IR
   Spf_approx(i) = cos(angle(Vs_approx(i) angle(Is_approx(i))))
   Spower_approx(i) = real(Vs_approx(i)*conj(Is_approx(i)))
   point(i) = i
   i = i+1
end
```

Acknowledgments

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