

Transmission Line Series Compensation for Wind Energy Transmission

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Abstract. Wind energy has demonstrated to be a clean, copious and absolutely renewable source of energy, and the large penetration of it into the power grid indicates that wind energy is considered an effective means of power generation. Transmission of wind energy from remote locations to load centers necessitates long transmission lines. Series compensation is a proven and economical transmission solution to address system power transfer strength, grid stability, and voltage profile issues of long transmission lines. In this paper, a programmable approach to determine the capacitive reactance of series capacitor and optimum location for its placement to achieve maximum power transfer has been presented. The respective program with sample solutions has been provided for real-time applications.

1. Introduction

Transmission grids across the globe have experienced noteworthy increase in renewable energy penetration primarily driven by utility scale wind turbines [1-3]. In more cases than not, regions concomitant with plentiful resource availability for wind power generation are far from the load centers [4-6]. Therefore long transmission networks are essential to deliver the renewable energy generation to the load centers. Transmission systems must be flexible to react to more diverse generation and load patterns. In addition, the economical utilization of transmission system assets is of vital importance to enable electric utilities in industrialized countries to remain competitive and to survive [7,8]. In developing countries, the optimized use of transmission system investments is also important to support industry, create employment, and utilize efficiently the scarce economic resources.

In order to confirm passable system performance in terms of large power transfers over long distances, system operators are considering series compensated transmission facilities to integrate remotely located wind generation and deliver power to load centers [9,10]. Series compensation on transmission lines is a proven and established technology in terms of adding series capacitors along the transmission line to reduce the "effective line impedance" thereby improving power transfer capability [11-13]. Series capacitors may be installed at one or both line ends of the transmission line. Line ends are archetypal capacitor locations, because it is usually possible to use space available in the substation. Consequently, this reduces installation/ capital cost. Alternatively series capacitors shall be installed at some central location on the line. Series capacitors placed at the line ends generate added complex protection problems than those installed at the center of the line.

2. Wind Energy Transmission



2.1. Remote Locations

One of the prevalent dares to wind power grid integration in many parts of the world is the necessity of developing new transmission lines to transfer power from wind farms, usually in remote lowly populated areas due to availability of wind, to high load locations, where population density is higher. The existing transmission lines in remote locations were not designed for the transport of large amounts of wind energy. As transmission lines become longer the losses associated with power transmission increase, as modes of losses at lower line lengths are exacerbated and new modes of losses are no longer negligible as the length is increased, making it tougher transferring huge loads over large distances.

2.2. Transmission Congestion

Transmission congestion occurs when power flow over a power transmission line exceeds its capacity, resulting a higher local marginal electricity prices in the electricity demand center, since more electricity must be supplied by local generators rather than less expensive, distant generators such as wind turbines. Escalating line capacity does not remove the transmission line congestion externality and only temporarily eases congestion. As far as wind power is concerned, they are more susceptible to transmission congestion than conventional power plants for two reasons. First, wind power must be transported over greater distances to meet sufficient demand, since it is typically windy at night when electricity demand is low. Second, conventional power plants are better connected with demand centers.

3. Compensated Transmission Lines

Electrical power transmission lines have three main parameters, such as resistance, inductance, and capacitance. The inductive reactance of a transmission line, which is directly proportional to the line inductance and the system frequency, is by far the most important line parameter because for normal line design, the power transfer capability is highly affected by its magnitude [14]. Hence, the inductive reactance of transmission lines becomes a problem of increasing importance when transmission line length continues to increase. A decrease in the line inductive reactance increases the power transfer capability.

3.1. Series Compensation

Series compensation schemes permit the connection of capacitors in series with the transmission lines, thus opposing directly the effect of the series inductive reactance of the lines. Series capacitors virtually reduce the length of the line, making it easier to keep all parts of the power system running in synchronism, and maintain a constant voltage level throughout the system. This method of improving the power transmission system performance is effective and inexpensive [9-15].

3.2. Thyristor Controlled Series Capacitor

The Thyristor Controlled Series Capacitor (TCSC) presented in Figure 1 is one such popular series compensation scheme. By controlling the firing of thyristor [14,15], one can change its apparent reactance smoothly and rapidly to manage the active power flow in the transmission line.

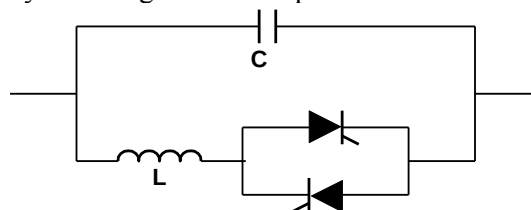


Figure 1. A Simple Circuit Model of TCSC

Assuming series capacitor compensation at a distance of x -km from the sending end as shown in Figure 2, the resultant generalized circuit constants of the compensated transmission line are generally given by equation (1) as

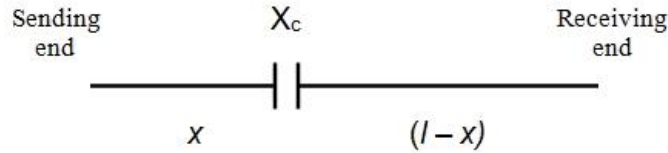


Figure 2. Compensated Transmission Line

$$\begin{vmatrix} A_c & B_c \\ C_c & D_c \end{vmatrix} = \begin{vmatrix} A_1 & B_1 \\ C_1 & D_1 \end{vmatrix} \begin{vmatrix} 1 & -iX_c \\ 0 & 1 \end{vmatrix} \begin{vmatrix} A_2 & B_2 \\ C_2 & D_2 \end{vmatrix} \quad (1)$$

where X_c = capacitive reactance of series capacitor

$$\begin{aligned} A_1 &= \cosh \gamma x; & A_2 &= \cosh \gamma(l-x); \\ B_1 &= Z_c \sinh \gamma x; & B_2 &= Z_c \sinh \gamma(l-x); \\ C_1 &= Y_c \sinh \gamma x; & C_2 &= Y_c \sinh \gamma(l-x); \\ D_1 &= \cosh \gamma x; & D_2 &= \cosh \gamma(l-x); \end{aligned}$$

With E_s and E_r as sending end and receiving end voltages, the received power, P_r can be written in the same form as that of an uncompensated as

$$P_r = \left(\frac{E_s E_r}{B_c} \right) \cos(\beta_o - \delta_o) - \left(\frac{A_c E_r^2}{B_c} \right) \cos(\beta_o - \alpha_o) \quad (2)$$

where E_s = magnitude of sending end voltage,
 E_r = magnitude of receiving end voltage,
 B_c = magnitude of the constant B_c
 A_c = magnitude of the constant A_c
 β_o = Argument of B_c
 α_o = Argument of A_c
 δ_o = Phase angle between E_s and E_r ,

and the maximum received power of the compensated line, $P_{\max}$ is also given as

$$P_{\max} = \left(\frac{E_s E_r}{B_c} \right) - \left(\frac{A_c E_r^2}{B_c} \right) \cos(\beta_o - \alpha_o) \quad (3)$$

3.3. Compensation Effect on Power Transfer

Among the four constants of the compensated line, only constants A_c and B_c are involved in the received power equation as seen in equation (2), hence any change in these will affect the received power [14,15].

From equation (1), the constant A_c can be written in a simplified form as

$$A_c = \cosh \gamma l - iX_c \left(\frac{1}{Z_c} \right) \cosh \gamma x \sinh \gamma(l-x) \quad (4)$$

One can see from equation (4) that the length of the transmission line (l), the location of the series capacitor from the sending end (x), the capacitive reactance of the series capacitor (X_c), the characteristic impedance of the transmission line (Z_c), and the propagation constant of the transmission line (γ) are the quantities that affect the value of the complex constant, A_c .

Likewise, the complex constant B_c (which is an impedance function) can be written in a simplified form after proper manipulation as

$$B_c = Z_c \sinh \gamma l - iX_c \cosh \gamma x \cosh \gamma(l-x) \quad (5)$$

Here also, once can see from equation (5) that the length of the transmission line, the location of the compensating device (i.e., the location of the series capacitor in this case), the capacitive reactance of the series capacitor, the characteristic impedance of the transmission line, and the propagation constant of the transmission line affect the value of the complex constant, B_c . Since for a transmission

line of specified length the characteristic impedance and the propagation constant are known quantities, the unknown quantities in equation (5) are the capacitive reactance of the series capacitor and the capacitor location from the sending end. Or in other words, particularly with respect to series compensation, the impedance of the compensated transmission line is affected by the location and the value of the compensating device; therefore, the changes in the line impedance because of series compensation, affect the power transferring capability of the compensated line.

4. Programmable Algorithm

4.1. Computational Flow

The functional steps of the proposed algorithm are listed out along with a flow chart as in Figure 3:

- Step 1: Determine the degree of percentage compensation
- Step 2: Compute the value of X_c as degree of compensation (%) = X_c/X_L .
- Step 3: Establish an arbitrary location for the series capacitor, say $x=0$ (from sending end).
- Step 4: Compute the values of A_c and B_c by using equations (4) and (5) respectively.
- Step 5: With the computed values of A_c and B_c , determine the power transfer for the specified location, x by using equation (2).
- Step 6: Likewise, assume different values of x until $x = l$, and compute the power transfer.
- Step 7: Compare the power transfers; the one with the highest magnitude is the optimum value of received power. The corresponding value of x is the optimum location for the placement of the series capacitor.

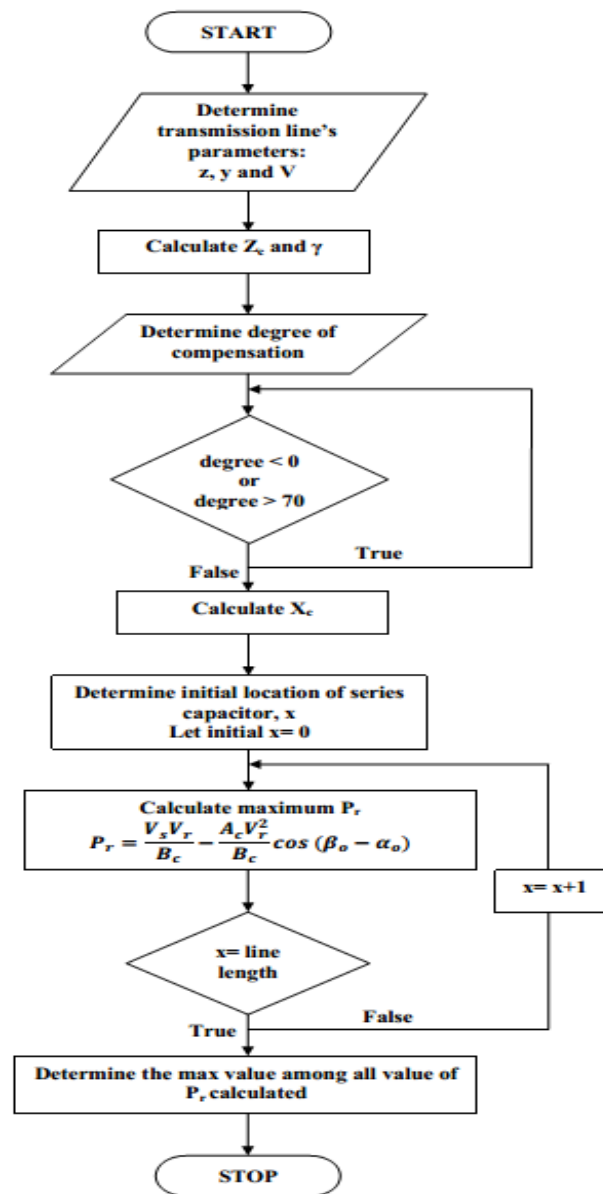


Figure 3. Flow Chart

4.2. C++ Programming

```

#include <cstdlib>
#include <iostream>
#include <stdio.h>
#include <math.h>
#define SIZE 99999
#define pi 3.141592654

using namespace std;

int main(int argc, char *argv[])
{
    int i,k;

    double length, Vs, Vr;
    double resistance, inductive, susceptance, cImpR, cImpI;
    double propagationR, propagationI, icImpR, icImpI;
    double a, b, c, d, m, n;
    double AcR, AcI, Ac, alpha, BcR, BcI, Bc, beta, min=1, max=0;
    double degree, Pmax[SIZE];
    double x,Xc;

    cout<<endl<<"PERCENTAGE COMPENSATION "<<endl<<endl<<endl;
    cout<<"Please enter the values for the parameters below: "<<endl<<endl;

    cout<<"Line length (km): ";
    cin>>length;
    cout<<"Resistance per unit length (Ohm/km): ";
    cin>>resistance;
    cout<<"Reactance per unit length (Ohm/km): ";
    cin>>inductive;
    cout<<"Susceptance per unit length (Mho/km): ";
    cin>>susceptance;
    cout<<"Sending end voltage (kV): ";
    cin>>Vs;
    cout<<"Receiving end voltage (kV): ";
    cin>>Vr;

    cImpR=sqrt(sqrt(pow(resistance,2)+pow(inductive,2))/(susceptance)) *cos
((atan(inductive/resistance)-(pi/2))/2);

    cImpI=sqrt(sqrt(pow(resistance,2)+pow(inductive,2))/(susceptance)) *sin
((atan(inductive/resistance)-(pi/2))/2);

    propagationR=sqrt(sqrt(pow(resistance,2)+pow(inductive,2))*(susceptance)) *cos
((atan(inductive/resistance)+(pi/2))/2);

    propagationI=sqrt(sqrt(pow(resistance,2)+pow(inductive,2))*(susceptance)) *sin
((atan(inductive/resistance)+(pi/2))/2);

    icImpR=1/(sqrt(pow(cImpR,2)+pow(cImpI,2))) *cos(-atan(cImpI/cImpR));
    icImpI=1/(sqrt(pow(cImpR,2)+pow(cImpI,2))) *sin(-atan(cImpI/cImpR));

    do
    {
        cout<<"Degree of Compensation (%)= ";

        cin>>degree;

        if (degree<0||degree>70){
            cout<<"Invalid Entry."<<endl<<"Range: 0
< Degree of Compensation < 70"<<endl;
        }
        while(degree<0||degree>70);

        Xc=degree/100*(inductive*length);

        a=propagationR*length;
        b=propagationI*length;

        for (x=1;x<=length;x++)
        {
            c=propagationR*x;
            d=propagationI*x;
            m=a-c;
            n=b-d;

            AcR=(1.0/2.0)*(exp(a)+exp(-a))*cos(b)+(Xc/4.0)*icImpR*((exp(c+m))*sin(d+n)-
            (exp(c-m))*sin(d-n)+(exp(-c+m))*sin(-d-n)-(exp(-c-m))*sin(-d-
            n)))+(Xc/4.0)*icImpI*((exp(c+m))*cos(d+n)-(exp(c-m))*cos(d-n)+(exp(-c+m))*cos(-d+n)-
            (exp(-c-m))*cos(-d-n));

            AcI=(1.0/2.0)*(exp(a)-exp(-a))*sin(b)-(Xc/4.0)*icImpR*((exp(c+m))*cos(d+n)-
            (exp(c-m))*cos(d-n)+(exp(-c+m))*cos(-d-n)-(exp(-c-m))*cos(-d-
            n)))+(Xc/4.0)*icImpI*((exp(c+m))*sin(d+n)-(exp(c-m))*sin(d-n)+(exp(-c+m))*sin(-d+n)-
            (exp(-c-m))*sin(-d-n));

            Ac=sqrt(pow(AcR,2.0)+pow(AcI,2.0));

            alpha=atan(AcI/AcR);

            BcR=(1.0/2.0)*cImpR*(exp(a)-exp(-a))*cos(b)-(1.0/2.0)*cImpI*(exp(a)+exp(-
            a))*sin(b)+(Xc/4.0)*((exp(c+m))*sin(d+n)+(exp(c-m))*sin(d-n)+(exp(-c+m))*sin(-
            d-n)+(exp(-c-m))*sin(-d-n));

            BcI=(1.0/2.0)*cImpR*(exp(a)+exp(-a))*sin(b)+(1.0/2.0)*cImpI*(exp(a)-exp(-
            a))*cos(b)-(Xc/4.0)*((exp(c+m))*cos(d+n)+(exp(c-m))*cos(d-n)+(exp(-c+m))*cos(-
            d+n)+(exp(-c-m))*cos(-d-n));

            Bc=sqrt((BcR*BcR)+(BcI*BcI));

            beta=atan(BcI/BcR);

            for(i=0;i<=(length+1);i++){
                Pmax[i]=(Vs*Vr)/Bc-(Ac*pow(Vr,2.0))/Bc*cos(beta-
                alpha);

                if (Pmax[i]>max){
                    max=Pmax[i];
                    k=x;
                }
            }
        }
    }
}

```

```

    }
    cout<<endl<<"Series Capacitor Reactance Value= "<<Xc<<" Ohm"<<endl;
    cout<<endl<<"Maximum Power Transfer= "<<max<<" Mw"<<endl;
    cout<<endl<<"Optimum Series Capacitor Location= "<<Xc<<" km away from sending
end"<<endl<<endl;

    system("PAUSE");
    return EXIT_SUCCESS;
}

```

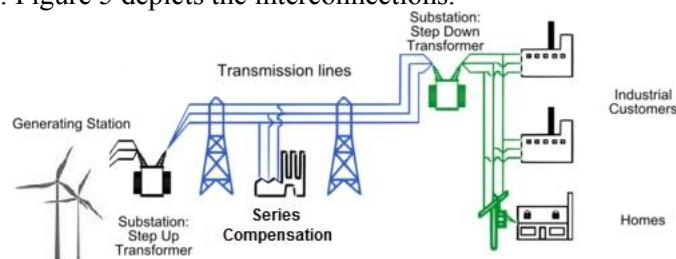
Figure 4. C++ Program

5. Application To A Prototype System

The suitability of the proposed programmable algorithm has been ascertained by applications to various transmission study systems and the proposed algorithm is found to be technically sound. The application to a prototype wind energy transmission system is presented here.

5.1. Prototype System

A remote wind farm is connected to a load center by means of a 320 km long 345 kV high voltage transmission line. TCSC compensation has been incorporated with a maximum permissible compensation of 50%. Figure 5 depicts the interconnections.

**Figure 5.** Wind Energy Transmission System

The parameters of the transmission line are:

Resistance	0.032 ohm/km
Inductive reactance	0.320 ohm/km
Susceptance	0.0000042 mho/km
Line length	320 km
Sending end voltage	345 kV
Receiving end voltage	345 kV (desired level)

5.2. Program Output

The line parameters are entered in the program through keyboard and mouse control. The degree of compensation is varied from 10% to 50% for equal sending end and receiving end voltages of 345 kV and the results are shown in Table 1.

For the given transmission line configuration, for a degree compensation of 25%, the maximum received power is found to be 1266.19 MW with the series capacitor reactance value of 28.0 ohms placed at a distance of 176 km from the sending end. The optimum location is not at the center of the transmission line but nearer to the middle towards the receiving end. Likewise, for every degree of compensation, the maximum power transfer is different with different capacitor reactance value. However, there is not much difference in the optimum location of the capacitor placement.

Table 1. Equal sending and receiving end voltages

Sending End Voltage: 345 kV Receiving End Voltage: 345 kV			
Degree of Compensation (%)	Series Capacitor Reactance (Ohms)	Maximum Power Transfer (MW)	Optimum Series Capacitor Location from Sending End (km)
10	11.2	1084.22	176
15	16.8	1138.93	176
20	22.4	1199.30	176
25	28.0	1266.19	176
30	33.6	1340.69	177
35	39.2	1424.08	177
40	44.8	1517.92	177
45	50.4	1624.09	178
50	56.0	1744.85	179

The screen shot of 25% compensation with equal sending and receiving end voltages is presented as in Figure 6.

```

Please enter the values for the parameters below:
Line length (km): 320
Resistance per unit length (Ohm/km): 0.032
Reactance per unit length (Ohm/km): 0.35
Susceptance per unit length (Mho/km): 0.0000042
Sending end voltage (kV): 345
Receiving end voltage (kV): 345
Degree of Compensation (%): 25

Series Capacitor Reactance Value= 28 Ohm

Maximum Power Transfer= 1266.19 MW

Optimum Series Capacitor Location= 176 km away from sending end

```

Figure 6. Screen shot with equal voltages

In order to know the effect of receiving end voltage on maximum power transfer and the capacitor location, the degree of compensation is varied from 10% to 50% for a sending end voltage of 345 kV and a receiving end voltage of 330 kV and the results are shown in Table 2.

Table 2. Unequal sending and receiving end voltages

Sending End Voltage: 345 kV Receiving End Voltage: 330 kV			
Degree of Compensation (%)	Series Capacitor Reactance (Ohms)	Maximum Power Transfer (MW)	Optimum Series Capacitor Location from Sending End (km)
10	11.2	1042.02	175
15	16.8	1094.95	175
20	22.4	1153.38	175
25	28.0	1218.22	176
30	33.6	1290.50	176
35	39.2	1371.52	176
40	44.8	1462.84	177
45	50.4	1566.38	177
50	56.0	1684.46	178

The screen shot of 25% compensation with unequal sending and receiving end voltages is presented in Figure 7.

```
Please enter the values for the parameters below:
Line length (km): 320
Resistance per unit length (Ohm/km): 0.032
Reactance per unit length (Ohm/km): 0.35
Susceptance per unit length (Mho/km): 0.0000042
Sending end voltage (kV): 345
Receiving end voltage (kV): 330
Degree of Compensation (%): 25

Series Capacitor Reactance Value= 28 Ohm
Maximum Power Transfer= 1218.22 MW
Optimum Series Capacitor Location= 176 km away from sending end
```

Figure 7. Screen shot with unequal voltages

While comparing the results of Tables 1 and 2, for the same amount of 25% compensation, due to the reduction in receiving end voltage to 330 kV, the maximum power transfer becomes 1218.22 MW at the same location. That means, a reduction of 47.83 MW is noticed due to the dip in the receiving end voltage. Similar situations happen for the different degrees of compensation.

Considering the magnitude of wind power generated, the degree of series compensation shall be adjusted to accommodate the excess generated power for transferring without upgrading the existing transmission facilities or constructing additional transmission lines. The developed program is highly flexible and it suitable for real-time applications.

6. Conclusions

This paper has deliberated the application of series compensation of long transmission lines intended for transferring wind energy from remote locations to the load centers. A programmable approach to determine the capacitive reactance of the series capacitor and the optimum location for its placement to achieve maximum power transfer has been presented. The respective program is suitable for real-time applications. From the prototype system test result, it is evident that series compensation techniques increase the power transferring capacity of existing transmission systems, and avoid the formation of new transmission lines to cope up with additional power transfer. Since formation of new transmission lines is very expensive compared to installing series capacitors for performing the same task, the series capacitor compensation is said to be cost effective. However, series compensation results in transmission line relaying and protection issues, an adverse effect on the power system stability, etc. and all these issues should be considered while implementing series compensation.

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