Abstract—Wind power is renewable, widely distributed plentiful, clean and produces no greenhouse gas emissions during operation. A large wind farm may consist of several hundred individual wind turbines which are connected to the electric power transmission network. However, the stochastic behavior of wind speeds leads to significant disharmony between wind energy production and electricity demand. The intermittency of wind seldom creates problems when used to supply up to 20% of total electricity demand, but as the proportion increases, a need to upgrade the grid, and a lowered ability to supplant conventional production can occur. Both reactive power and voltage control are important under varying operating conditions of wind farm as electricity generated from wind power can be highly variable at several different timescales: hourly, daily, or seasonally. To optimize reactive power flow and to keep voltages within limit, an optimization method is proposed in this paper. This algorithm has been tested under practically varying conditions simulated on a test system. The results are obtained on a system of 110 bus real life equivalent power system. The approach considers the reactive power limits of wind generators and co-ordinates the transformer taps. The result shows the efficiency of the proposed method.

Keywords—wind power, optimization, sensitivity matrix, reactive power, tap changer

I INTRODUCTION

One of the most promising and important renewable energy resources in the world is wind energy. The total amount of economically extractable power available from the wind is considerably more than human power use from other sources. Over the past five years the average growth in new installations has been over 27 percent each year. Wind farm installed in the distribution system can decrease the investments for the distribution system expansion, but the intermittent characteristics and unpredictable nature of wind power generation impact whole network voltages, frequency and generation. In the emerging energy scenario penetration of renewable energy sources have to be in synchronous with the demand requirements. The biggest challenge here is to control reactive power supply and maintain acceptable grid voltages. Wind farms have to supply not only active power, but also to supply/consume the reactive power to/from the grid. So that the wind power installations can participate in the grid frequency and bus voltage controls. So the electrical parameters like reactive power, real power losses and voltages of the distribution network have to be maintained [1-4].

II THE PROBLEM FORMULATION

Generally the wind farms are located at geographical suitable locations (may be remote from load centers). The wind farm consists of a number of wind generators of smaller sizes connected through a transformer to typically around 33 kV. A number of generators connected along the 33 kV form groups and 33 kV line is connected to grid at 220 kV. The wind generator active power availability is random type from almost nil to its full rating for different groups during different times. Each wind generator has limited reactive power capability with different type of interconnectivity (different types of generator and power electronics connection) through the transformers having fair taps range for co-ordination with the grid system.

We are considering a wind farm system connected to grid where grid is considered as an equivalent generator along with all the wind generators. The grid generator delivers and absorbs real and reactive power depending on the system load and availability of wind generation. These wind generators form groups spread geographically at different locations connected through transformers to H.T. (typically 33 kV) cable. Each generator terminal voltage has limited range and also the transformer tap ranges. The H.T. line is further connected to grid at remote location through a transformer. We can consider that there are few locations where Switchable VAR compensation (SVC), typically capacitor banks/reactor for voltage improvement and overvoltage protection. We consider 1, 2, ..., g the total number of generators buses, g+1,...,g+s are the SVC buses, g+s+1,...,n are the remaining buses. The total numbers of control variables are k with I, 2...t number of on-load-tap-changing (OLTC) transformers, t+1, t+2...t+g generator excitations and t+g+1...s SVCs, (k=t+g+s). [5-6]

A) Reactive power optimization problem: proposed formulation

The model selected for the reactive power optimization in a wind farm uses linearized sensitivity relationships to define the optimization problem. Objective considered are:

Minimize the sum of the squares of the voltage deviations from desired voltages at all load buses (objective $V_{\text{desired}}$)

$$V_e = \sum_{j=g+1}^{n} (V_{j}^{\text{desired}} - V_{j}^{\text{actual}})^2$$

in the system. (1)

For this objective the constraints are the linearized network performance equations relating the control and dependent variables and the limits on the control and dependent variables. The control variables are:
The transformer tap settings \((\Delta T)\)
- The generator excitation settings \((\Delta V)\)
- The Switchable VAR Compensator (SVC) settings \((\Delta Q)\)

These variables have their upper and lower limits. Changes in these variables affect the distribution of the reactive power of the wind generator and therefore change the reactive power at generators, the voltage profile and thus the voltage stability of the system. The dependent variables are:
- The reactive power outputs of the generators \((\Delta Q)\)
- The voltage magnitude of the buses other than the generator buses \((\Delta V)\)

These variables also have their upper and lower limits. In mathematical form, the problem is expressed as:

\[
\text{Minimize} \quad \nu_e = C x \\
\text{Subject to} \quad b^{\text{max}} \leq x \leq b^{\text{min}} \\
\text{and} \quad x^{\text{max}} \leq x \leq x^{\text{min}} \quad (2)
\]

Where \(C\) is the row matrix of the linearized objective function sensitivity coefficients, \(S\) is the linearized sensitivity matrix relating the dependent and control variables, \(b\) is the column matrix of linearized dependent variables, \(x\) is the column matrix of the linearized control variables, \(b^{\text{max}}\) and \(b^{\text{min}}\) are the column matrices of the linearized upper and lower limits on the dependent variables and \(x^{\text{max}}\) and \(x^{\text{min}}\) are the column matrices of linearized upper and lower limits on the control variables.

The linear programming technique is now applied to the above problems to determine the optimal settings of the control variables.

The control vector in incremental variables is defined as
\[
x = [\Delta T_1, \ldots, \Delta T_t, \Delta V_1, \ldots, \Delta V_g, \Delta Q_{g+1}, \ldots, \Delta Q_{g+s}]^T \quad (3)
\]
and the dependent vector in incremental variables as
\[
b = [\Delta Q_1, \ldots, \Delta Q_g, \Delta V_{g+1}, \ldots, \Delta V_{g+s+1}, \Delta V_a]^T \quad (4)
\]

### B) Computation of Sensitivity Matrix \((S)\)

The sensitivity matrix \(S\) relating the dependent and control variables is evaluated in the following manner. Considering the fact that the reactive power injection at a bus does not change for a small change in the phase angle of the bus voltage, the relation between the net reactive power change at any node due to change in the transformer tap settings and the voltage magnitudes can be written as

\[
\frac{\partial Q_k}{\partial T_{km}} = \frac{2}{a^3} V_k^2 y_{km} \sin \alpha_{km} + \frac{1}{a^2} y_{km} V_k V_m \sin(\delta_k - \delta_m - \alpha_{km}) \\
\frac{\partial Q_m}{\partial T_{km}} = \frac{1}{a^2} y_{km} V_k V_m \sin(\delta_m - \delta_k - \alpha_{km}) \\
\frac{\partial Q_r}{\partial T_{km}} = 0, \quad r \neq k, m \quad \text{and},
\]

\[
\frac{\partial Q_k}{\partial V_k} = \frac{Q_k}{V_k} - B_{sk} V_k \\
\frac{\partial Q_k}{\partial V_m} = Y_{km} V_k \sin(\delta_k - \delta_m - \theta_{km})
\]

By transferring all the control variables to the right hand side and the dependent variables to the left hand side and rearranging eq. (7):

\[
\begin{bmatrix}
\Delta Q_g \\
\Delta V_s \\
\Delta V_r
\end{bmatrix} = \begin{bmatrix}
S_1 & S_2 & \Delta T_t \\
S_3 & S_4 & \Delta V_g \\
\end{bmatrix}
\]

C) Computation of Objective Function \(V_{\text{desired}}\)

\(\nu_e = \sum_{j=g+1}^{n} (V_{\text{desired}} - V_{\text{actual}})^2\) sensitivities \((C)\) with respect to Control Variables

i) Transformer model:

Considering a transformer connected between buses \(k\) and \(m\) with taps on bus \(k\), the real and reactive power injections into the buses \(k\) and \(m\) are \(P_k, Q_k, P_m\) and \(Q_m\), as shown in Figure 1.

![Transformer representation with tap \(T_{km}\) on bus \(k\)](image)

A small change in the tap of the transformer between buses \(k\) and \(m\) results in an incremental power flow in this line, thereby changing the power injections into the end buses, as shown in Figure 2.

\[
\frac{\partial V_e}{\partial T_{km}} = \sum_{j=g+1}^{m} 2(V_{\text{desired}} - V_{\text{actual}})(-S_{jm})
\]

Where \(m=1,2,\ldots,t\) for calculating the objective function sensitivities with respect to transformer taps, and \(S_{jm}\) is corresponding elements in equation.
Fig 2. Transformer representation with incremental power injection errors

\[ \frac{\partial V_m}{\partial V_m} = \sum_{j=g+1}^{n} 2(V_j^{desired} - V_j^{actual})S_{jm} \]

Where \( m = t+1, t+2 \ldots t+g \) for calculating the objective function sensitivities with respect to generator excitations

\[ \frac{\partial V_m}{\partial Q_m} = \sum_{j=g+1}^{n} 2(V_j^{desired} - V_j^{actual})S_{jm} \]

Where \( m = t+g+1 \ldots k \) for calculating the objective function sensitivities with respect to SVCs [6].

D) Computational Procedure for Reactive Power Optimization

A computer program has been developed to solve the linear programming problem. [5-6]. From results of this algorithm we will be able to find active and reactive power control at dispatch center. In the day-to-day operation of the wind systems, the flowchart used to obtain the optimal reactive power allocation in the system for improvement of voltage profile is shown in fig 3.

III SYSTEM STUDIES

The proposed approach has been tested on a 111-bus wind system using the objective \( V_{desired} \). The system is a practical equivalent system. The results are obtained for this wind system under different conditions to maintain voltage profile in respect of variable wind generation.

The system single line diagram is shown in Figure 5 and its data is given in Table 1. The system has 55 generator buses (54 wind generator and 1 grid equivalent generator) and 55 other load buses. Wind farm has 3 groups of wind generators with each wind generator of same rating. First group has 24 generators, second group has 18 generators and third group has 12 generators. The system total peak generation from wind is about 51.3 MW, 21.6 MVAR. At bus 57, ten capacitors banks of 1 MVAR each are assumed to be connected.

Case studies

The wind generation can vary from 0%-100%. So in this paper a total of 5 cases are considered to find optimum setting of reactive power controllers which maintains acceptable system voltage profile. Voltage profile, reduction in losses and reactive power flow is compared before and after optimization to check the efficiency of the method. Bus voltages should be in the range of 0.975-1.05 pu. Wind Generator should not cross its reactive power limit (0.4 MVAR to -0.4 MVAR) in each case. P-Q characteristic of wind generator is shown in Figure 4.

The proposed method is applied to different cases having different generation patterns varying from 0.885 MW to 0.19 MW in every group to consider variation in wind patterns. In all these cases initially it is assumed that all the transformers taps are at 1.0 nominal value and generator voltage at 1.0 and no VAR compensation. For various cases the random availability of wind power considered is given in detail in Table 2.
Before optimization there were 33 under voltage buses having voltage below 0.975 pu, 12 generators were exceeding their $Q_g$ maximum limits. After optimization there is no bus violating voltage limits and no generator is violating its $Q$ limits. Losses are reduced from 0.3833 MW to 0.2502 MW, a reduction of 34.72 %. Voltage profile and reactive power is shown in Figure 6 and Figure 7.

![Voltage profile before and after optimization](image)

**Table 1. System data**

1. **Main transformer (1)**
   - 220/33 kV 100 MVA
   - $X = 12.5\%$
   - Taps = each step 0.00625 (range 1.1pu to 0.90 pu)

2. **Main Generator (1) grid equivalent**
   - 220 kV 100 MVA

3. **Generator Transformers (54 no’s)**
   - 33/0.400 kV, 1 MVA
   - $X = 9.474\%$ (on its own base)
   - Taps = each step 0.025 (range 1.1pu to 0.90 pu)

4. **Wind Generators (54 no’s)**
   - 400 V, 0.95 MW

5. **220 kV OH line (bus 1-56, 8km)**
   - $R = 0.07744\Omega/km$, $X = 0.39998\Omega/km$
   - $b = 2.8512\mu mho/km$

6. **33 kV OHD**
   - $R = 0.27088\Omega/km$, $X = 0.45\Omega/km$
   - $b = 2.9384\mu mho/km$

7. **33 kV cable**
   - $R = 0.1356\Omega/km$, $X = 0.108\Omega/km$
   - $b = 131.94\mu mho/km$

8. **33 kV OHD line lengths**
   - bus 57-58: 8km, bus 57-82: 6km, bus 57-100: 4km

9. **33 kV cables (300 meters)**
   - bus 58-59, bus 59-60, bus 80-81
   - bus 82-83, bus 83-84, bus 98-99
   - bus 100-101, bus 101-102, bus 110-111

**Load (buses 56, 57)**

- Bus 57: 25 MW 15 MVAR
- Bus 56: 30 MW 15 MVAR
- (10 MVAR capacitor bank with 1 MVAR step size is connected at bus 57)

**Case A: 20-30% wind power generation**

- Group 1: 30% 0.285 MW
- Group 2: 25% 0.2375 MW
- Group 3: 20% 0.19 MW

![Wind network](image)
**Case B: 30%-40% wind power generation**

Group 1: 40% 0.38 MW  
Group 2: 35% 0.3325 MW  
Group 3: 30% 0.285 MW

Before optimization there were 33 under voltage buses having voltage below 0.975 pu, 12 generators were exceeding their Qg maximum limits. But after optimization there is no bus violating voltage limits and no generator is violating its Q limits. Losses are reduced from 0.4857 MW to 0.3715 MW, a reduction of 23.51%. Voltage profile and reactive power is shown in Figure 8 and Figure 9.

**Case C: 40%-60% wind power generation**

Group 1: 60% 0.57 MW  
Group 2: 50% 0.475 MW  
Group 3: 40% 0.38 MW

Before optimization there were 33 under voltage buses having voltage below 0.975 pu, 12 generators were exceeding their Qg maximum limits. But after optimization there is no bus violating voltage limits and no generator is violating its Q limits. Losses are reduced from 0.7932 MW to 0.6682 MW, a reduction of 15.76%. Voltage profile and reactive power is shown in Figure 10 and Figure 11.

**Case D: 60%-80% wind power generation**

Group 1: 80% 0.76 MW  
Group 2: 70% 0.665 MW  
Group 3: 60% 0.57 MW

Before optimization there were 26 under voltage buses having voltage below 0.9750 pu, 12 generators were exceeding their Qg maximum limits. But after optimization there is no bus violating voltage limits and no generator is violating its Q limits. Losses are reduced from 1.3146 MW to 1.2057 MW, a reduction of 8.28%. Voltage profile and reactive power is shown in Figure 12 and Figure 13.
Case E: 80%-90% wind power generation
Group 1: 90% 0.885 MW
Group 2: 85% 0.8075 MW
Group 3: 80% 0.76 MW

Before optimization there were 23 under voltage buses having voltage below 0.975 pu, 12 generators were exceeding their Qg maximum limits. But after optimization there is no bus violating voltage limit and no generator is violating its Q limits. Losses are reduced from 1.8028 MW to 1.6480 MW, a reduction of 8.59%. Voltage profile and reactive power is shown in Figure 14 and Figure 15.

Table 2 and figure 16 is showing the summary of results obtained by the proposed approach. Results are showing efficiency of the methodology when generator excitation, transformers taps and VAR setting are considered as control variables. The analysis is enabling us to understand the behavior of the power flow of the grid under different scenarios.

This method is:
• Maintaining reactive power generation of wind generator within limit
• Coordinating all the transformer taps
• Improving voltage profile
• decreasing overall system losses for all the cases

V CONCLUSIONS

In this paper an optimization technique for improved operation of wind system and ensuring a good network voltage profile has been presented. The method proposed is very useful in wind farms, as evident from the results. The V\text{\textit{desired}} objective is giving acceptable results both under light load and peak load conditions. The movement of control variables is consistent with V\text{\textit{desired}} objective. The computational time for each VAR control iteration is about 2 sec. Application of the proposed method can avoid wind system failures. This method can easily be applied to any wind farm irrespective of its size and also applicable to any other DG type.
VI REFERENCES


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