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Impact of Wind Energy Modeled Distributed Generation on Reconfiguration of Unbalanced Radial Distribution System

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Abstract: The aim of the study is to investigate the impact of wind energy modeled distributed generation on reconfiguration of unbalanced radial distribution system for voltage profile improvement and power loss minimization. By installing Distributed Generators (DG), reliability and voltage profile of unbalanced radial power distribution system can be improved with reduction of power losses. Unbalanced radial power distribution systems usually cause low power quality, low voltage profile, more investment and high operating costs. Feeder reconfiguration is a good technique to balance these systems to improve voltage profile and to reduce the power losses. In this paper a 0-1 integer programming optimization method for reconfiguration of unbalanced radial distribution system with wind energy modeled distributed generation, for improvement of voltage profile and power loss minimization is proposed. The results obtained with the proposed methodology for a practical system demonstrates its applicability.

Key words: DG, integer programming, optimization, power loss, practical system, voltage proile

INTRODUCTION

Distribution feeders supply power to various types of loads namely residential, commercial, industrial and agricultural. Each feeder has different loads and different load variations. Consequently peak loads at different feeders occur at different times. A configuration set for minimum loss at a certain instant is no longer a minimum loss configuration at a different instant of time. Hence there is a need for feeder reconfiguration for loss minimization whenever there is a change in the system-loading pattern (Celli *et al.*, 2005; Nakanishi *et al.*, 2000). To improve the reliability, efficiency and service quality distribution networks should be automated. Automation is possible with advanced microprocessor control technology. Under normal operating conditions systems will be reconfigured to reduce the power losses and under condition of permanent failure networks will be reconfigured to restore the services (Wu *et al.*, 1991; Enrico *et al.*, 2006). Different algorithms have been used to solve the reconfiguration problem: combinational optimization with discrete branch and bound methods, expert system techniques and heuristic methods (Wu *et al.*, 1991). First work on reconfiguration was presented by Merlin and Back (an integer mixed non linear optimization). But it requires checking a great number of configurations for a real sized system.

Castro proposed characteristic of the neighborhood structure, which reduces the number of reconfigurations. But the CPU time is more. Castro and Franca propose modified heuristic algorithms to restore the service and load balance. Wang and RIzy proposed an integrated scheme for distribution system loss minimization with consideration of line capability limits via reconfiguration (Enrico *et al.*, 2006). Lieu and vent proposed an application of expert system to the restoration of distribution system by group restoration, zone restoration and/or load transfer. Morelato and Nonticelli proposed a heuristic search approach based on a binary decision tree. In this approach the search space is quite large and a sub optimal solution is found. Taylor and Lubkeman proposed a heuristic search strategy to handle feeder reconfiguration for overloads, voltage problems and for load balancing (Ahmed and István, 2005). This study extends these works by considering the comprehensive switching problem.

Distributed generation is related with the use of small generating units to meet load requirements installed in strategic points nearer to load centers (Carmen *et al.*, 2003). The technologies applied in DG comprise gas turbines, Photovoltaic Systems (PV), fuel cell, wind energy etc. the planning of the distribution network for DG requires definition of several factors, such as number of DGs to be installed, technology to be used, location of each DG and capacity of each unit etc. the selection of capacity and number of DGs, location of DGs is a complex combinational optimization problem (Ackermann *et al.*, 2001).

This study presents the impact of wind energy modeled DG units on voltage profile and electric power losses of Unbalanced Radial Power Distribution Systems (URDS). On the same system reconfiguration based on

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0-1 integers programming optimization method is proposed for further improvement of voltage profile and minimization of the power losses. This method uses multiple switching at a time and finds the overall minimum loss network configuration.

MATERIALS AND METHODS

This study was conducted in 2009 in the Electrical Engineering Department of TRR Engineering College, inole, medak district, Hyderabad, India.

Impact of wind energy modeled Distributed Generation (DG): Distributed generators in unbalanced distribution systems perform the tasks like load voltage stabilization, uninterruptible power supply, reactive power support for power factor correction, balance the source voltages in case of unbalanced load system and active power support.

If the Distributed generators are correctly installed at optimal locations and if units are correctly coordinated, they will have positive impact in unbalanced Distribution system. Main use of DG is for generation back up. Another popular advantage of DG is injection of excess power into unbalanced distribution network when the DG capacity is higher than the local loads. For radial analysis of the unbalanced distribution systems, DGs can be modeled as negative loads. That means negative active and reactive power injection independent of the system voltage. Distribution systems are also regulated through tap changing transformers, by using voltage regulators and capacitors in feeders (Ackermann *et al.*, 2001).

Lot of research work has been done on balanced distribution systems reconfiguration but not on wind energy modeled distributed generators impact on unbalanced radial power distribution network reconfiguration.

The 0-1 integer programming: The 0-1 integer-programming problem may be defined as the problem of maximizing or minimizing a linear function subject to linear constraints. The constraints may be equalities or inequalities. Occasionally, the maximum occurs along an entire edge or face of the constraint set, but then the maximum occurs at a corner point as well. Not all 0-1 integer-programming problems are so easily solved. There may be many variables and many constraints. Some variables may be constrained to be nonnegative and others unconstrained. Some of the main constraints may be equalities and others inequalities. However, two classes of problems, called here the standard maximum problem and the standard minimum problem, play a special role. In these problems, all variables are constrained to be nonnegative, and all main constraints are inequalities.

We are given an m-vector,
$b = (b_1, . . . , b_m)^T$, An n-vector,
$c = (c_1, . . . , c_n)^T$, and an m×n matrix of real numbers,

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}$$

The standard maximum problem: Find an n-vector, $x = (x_1, . . . , x_n)^T$, to maximize $c^Tx = c_1x_1+...+c_nx_n$ subject to the constraints

$$a_{11}x_1+a_{12}x_2+...+a_{1n}x_n \le b_1$$
$$a_{21}x_1+a_{22}x_2+...+a_{2n}x_n \le b_2$$
$$a_{m1}x_1+a_{m2}x_2+...+a_{mn}x_n \le b_m$$

and

$$x_1 \ge 0, x_2 \ge 0..., X_n \ge 0$$

The standard minimum problem: Find an m-vector, $y = (y_1, . . . , y_m)$, to minimize $y^Tb = y_1b_1 + \cdots + y_mb_m$ subject to the constraints

$$y_1a_{11}+y_2a_{21}+...+y_ma_{m1} \ge c_1$$
$$y_1a_{12}+y_2a_{22}+...+y_ma_{m2} \ge c2$$
$$\vdots \qquad \text{(or } ytA \ge cT$$
$$y_1a_{1n}+y_2a_{2n}+...+y_ma_{mn} \ge cn$$

and

$$y_1 \ge 0, y2 \ge 0, ..., ym \ge 0 \qquad \text{(or } y \ge 0)$$

$$a_{11}y_1+a_{12}y_2+...+a_{1n}y_m \le c_1$$
$$a_{21}y_1+a_{22}y_2+...+a_{2n}y_m \le c_2$$
$$a_{m1}y_1+a_{m2}y_2+...+a_{mn}y_m \le c_n$$

and

$$y_1 \ge 0, y_2 \ge 0..., Y_n \ge 0$$

Problem formulation: The objective of reconfiguration technique is to minimize the power flows in order to minimize the power losses. By taking voltage constraints in to consideration, a simple 0-1 integer programming technique is developed. Optimization of power flows that result in the minimum power loss configuration is possible by penalizing flows through higher resistance branches and encouraging flows through lower resistance branches.

Generally optimal power flow requires solving a set of nonlinear equations, describing optimal and/or secure operation of an unbalanced power distribution system expressed as

$$\text{Minimize} \qquad F(x,u) \qquad (1)$$

While satisfying $g(x,u)=0$ (2)

$H(x,u) \leq 0$ (3)

Where; g(x,u): set of nonlinear equality constraints (power flow equations);

H(x,u): set of inequality constraints of bus voltage magnitudes and phase angles, as well as MVAr loads, fixed bus voltages, line parameters, and so on;
X is a vector of optimal solution to minimize power loss function;
U: a vector of control variables.
The vector 'u' includes the following.
Real and reactive power generation of source;
Phase shift angles of 3 phases;
Net interchange of active and reactive power between DG and unbalanced distribution network;
Load MW and MVAr of each phase
DC power flows of DG;
Control voltage settings;
Load tap changer transformer settings.

Network reconfiguration problem of the unbalanced distribution system: The problem is formulated as a multi objective combinatorial optimization problem.

A radial unbalanced distribution system with k nodes and with a known topology, problem is to find an optimal switching configuration among all possible combinations R_j with the switching changes, that minimizes the objective function and that doesn't disturb the network load flow and operational constraints.

$$\text{Min } C(x,R_i) \quad (4)$$

Subject to:

$$F(x,R_i) = 0 \quad (5)$$

and

$$G(x,R_i) \leq 0 \quad (6)$$

Where; $C(x,R_i)$ is the objective function to be minimized. $F(x,R_i)$ is the vector of equality constraints and represents the load flow equations. $G(x,R_i)$ is the vector of inequality constraints and corresponds to operational constraints for the network.

x = (P, Q, V) where P and Q represents active and reactive power s of receiving end of branches and v is the magnitudes of the voltage at system nodes.

[Constraints]
$F(x_1, x_2)=0$, $G(x_1, x_2) \leq 0$

Where C_1, C_2 are mean distribution power loss and feeder power balance respectively. Here x_1 represents discrete variables for switch status and x_2 represents continuous variables to calculate power flow of unbalanced distribution system.

The objective function to be minimized can be expressed as

$$C(x,Ri) = \sum_{i=1}^{k-1} Z_{ia} \frac{P_{ia}^2 + Q_{ia}^2}{V_{ia}^2} + \sum_{i=1}^{k-1} Z_{ib} \frac{P_{ib}^2 + Q_{ib}^2}{V_{ib}^2} + \sum_{i=1}^{k-1} Z_{ic} \frac{P_{ic}^2 + Q_{ic}^2}{V_{ic}^2} \quad (7)$$

Where; *i* is any feeder branch; *k* is number of network busses; Z_i is the pu impedance of the branch.

Power flow methods: Traditional load flow methods are not enough to apply on unbalanced radial distribution systems. Load flow calculation method should use low memory resources and should have good convergence. Various methods are ladder method, current summation method, power summation method. In these, power summation methods have better convergence characteristics.

Power summation method: it has two processes in first process a node is taken and the active and reactive power demand from the network is determined seen from second process. This process is initialized assuming a voltage profile. In second process, using the calculated powers in previous process modules of the voltages in nodes are recalculated. Convergence will be checked with voltage magnitudes only. From magnitudes it is possible to calculate respective angles.

$$V_i^2 + A_i V_i^2 + Bi = 0 \quad (8)$$

$$A_i = 2(P_i R_i + Q_i X_i) - V_{i-1}^2 \quad (9)$$

$$B_i = (P_i^2 + Q_i^2)(R_i^2 + X_i^2) \quad (10)$$

$$\tan \beta_i = \frac{P_i X_i + Q_i R_i}{(P_i R_i + Q_i X_i + V_i^2)} \quad (11)$$

$$B_i = ang(V_{i-1}) - ang(V_i) \quad (12)$$

$$P_i = P_{Li} + \sum^{NAI} P_k + \sum^{NAI} X_k \frac{P_k^2 + Q_k^2}{V_k^2} \quad (13)$$

$$Qi = Q_{Li} + \sum^{NAI} Q_k + \sum^{NAI} X_k \frac{P_k^2 + {}_k^2}{V_k^2} \quad (14)$$

Where;
V_{i-1}, V_i : Voltage magnitudes at nodes i-1 and i
R_i, X_i : Resistance and inductive reactance of section i
N_{Ai} : set of nodes fed directly fed from node i
β_i : Voltage angle difference between i-1 and i

Proposed methodology: Network reconfiguration is the procedure of varying the topological structure of distribution feeders by changing the open/closed states of the sectionalizing and tie switches. Reconfiguration is used to reduce real power losses, relieve network from overloads (load balancing) and improve system security. In order to achieve a radial operation scheme, certain number of closed and normally open switches will be rearranged. As the number switches are generally high, the number switching combinations are also high, making the feeder reconfiguration complex and time-consuming process. Due to addition of Distributed generator to a radial structured feeder, reconfiguration in an unbalanced distribution system will be more complex (Wu *et al.*, 1991; Dobariya and Khaparde, 2007).

In this study a simplified reconfiguration approach using a 0-1 integer programming technique is developed and applied to an unbalanced distribution system containing two Distributed generators to demonstrate its applicability. A non-conventional energy source (wind energy) has been modeled as the distributed generator. A simulation circuit has been developed to study the impact of Distributed generation on power quality of unbalanced distribution system.

Each element of the unbalanced distribution system is assumed to contain a sectionalizing switch so that any element can be switched for reconfiguration purpose. While the proposed reconfiguration technique is applied, each element is described by either 0 or 1 variable. 0 is assigned to an element when it is in open position and 1 is assigned when it is in closed position.

To solve the above objective function by 0-1 integers programming by identifying the variable (0 or 1) for each element and power loss function for each element, the algorithm proposed is as follows.

RESULTS AND DISCUSSION

Algorithm proposed:

- Each node of the circuit is assigned with another variable 1 or (-1). If the node is a switching node then assign (1) and if the node is a neighboring node then assign (-1). Each variable of the circuit is associated with a variable y_i, which takes the value 1 if the node is a switching node and -1 if the node is neighboring node of the circuit.
- Two DGs are modeled as positive active and reactive power suppliers in the objective function. Load currents are identified that contribute to the loss function in each element of the circuit.
- Load voltages are identified that contribute the power loss function of each element of each circuit
- Find the second order and third order terms of power loss function of each circuit by finding all possible combinations of elements. The number of second order terms in the loss function of a circuit can be obtained by finding all possible combinations of 0-1 integer variables x_i taken two at a time. The number of first order terms would be equal to the number of 0-1 variables in a circuit. The coefficients contributed y first order terms can be obtained as follows. The coefficient x_m contributed by an element is equal to $x_i[I_{nm}^2 + 2y_m I_{nm}(I_{Li})]$ where I_{Li} is equal to sum of the load currents that contribute to the current in element *i*.
- Determination of the power loss function: now the coefficients of the terms in power loss function of a circuit can be obtained by taking summation of contributions of the various elements in the circuit to the respective coefficients.
- Minimize the above objective function by 0-1 integer programming. To solve the optimization problem use generalized interactive non-linear optimizer.
- Based on the solution determine the elements to be switched.
- end This method uses multiple switching at a time and finds the overall minimum loss network configuration

Simulation of DG: In simulation, a neutral clamped inverter circuit with a DC storage device has been chosen to present compensation topology in Fig. 1.

It consists of a renewable wind energy source and two capacitors at the DC side of the inverter. The junction of the circuits is connected to the neutral point of the load. The clamped neutral allows the path for the zero sequence component of current. Therefore three currents will be controlled independently.

DG and compensator parameters:
DC capacitors (C1, C2): 2000 µF each;
Interface Inductors: 20 mH, 0.2Ω each.

DG simulation results: The distorted source voltages and currents without compensation are given in Fig. 2.

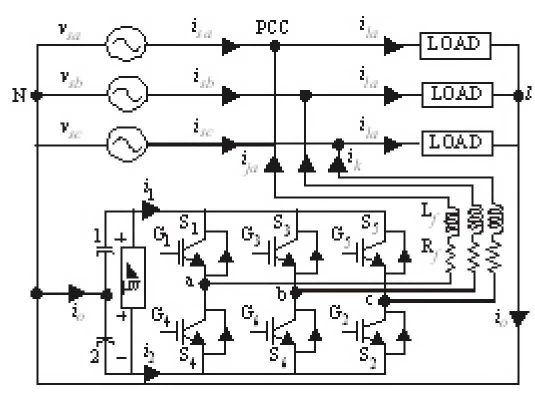

Fig. 1: URDS with DG and inverter

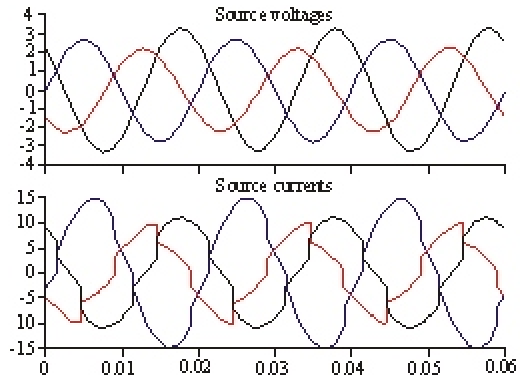

Fig. 2: Source voltages and currents without compensation

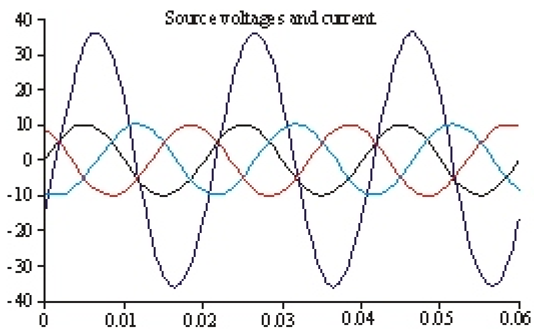

Fig. 3: Source voltages and currents with compensation

The distorted source voltages and currents with compensation are given in Fig. 3.

The fundamentals of the voltages have an unbalance of ±10%. The total harmonics distortion in phases a, b and c are 5, 7 and 8% respectively.

Wind turbine model in grid simulation program: When the steady state voltage level is of interest, the wind turbine outputs, active and reactive power, can be described as functions of mean wind speed. In the grid simulation program, they can simply be represented as sources of active and reactive power. Active power is given by the static power curve of the wind turbine, the relation between mean wind speed and the produced active power, while the amount of reactive power exchanged with the grid is decided according to the control objectives of the specific turbine. For fixed speed systems, as well as for a variable-speed system with an induction machine and rotor resistance control, the reactive power is a function of the active power according to the P-Q relation of the generator used. No-load reactive power consumption is typically compensated for with a capacitor bank. For the other variable-speed turbines, reactive power is independent of active power and can be put to an arbitrary value, often zero. Dynamic voltage variations of such a magnitude that the Pst level on the grid could be substantially affected mainly originate in fixed speed systems. A reasonably correct prediction of dynamic behavior up to a frequency of about 10 - 20 Hz is of interest. A model of a stall-regulated, fixed-speed system is described. A model of an active stall-regulated turbine can be obtained by slightly modifying a stall-regulated model, since the characteristics of these two systems, with respect to dynamic voltage variations, are fairly similar. A model of a pitch-regulated, fixed speed wind turbine is more complicated. Since a pitch-regulated, fixed-speed system gives rise to major problems with dynamic voltage variations, apart from large mechanical stresses, it is no longer installed to the electric grid and other systems are used instead. A model of such a system is, thus, of little practical value. Since variable-speed systems have, in most cases, a low impact on dynamic voltage variations, generally lower than the stated limits, dynamic voltage variations prediction models of these systems seem to be of little practical interest. Moreover, the behavior of these systems is mainly dependent on the control algorithms used. These vary depending on the turbine manufacturer and are usually kept confidential. High harmonic distortion is a problem that can occur when variable-speed systems are used. However, with a properly designed harmonic filter, this problem can be avoided. Other parts of the wind turbine are of little practical interest here.

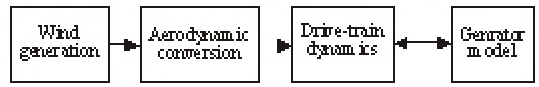

Fig. 4: A wind turbine model structure

Wind turbine modeling: Based on the discussion in the preceding section the decision was made to develop a model of a stall-regulated, fixed-speed wind turbine system. The following sections describe individual building blocks of the modeled system.

Structure of the system: The model of the overall wind turbine system integrates several building blocks. The basic structure of the model is given in Fig. 4.

As seen, there is no controller or visible feedback loops in the presented system structure. The stall-regulated, fixed-speed system is self-controlled, i.e. its operational characteristics keep the system running within operational limits without the need for an external controller. The logic that controls starting up and shutting down of the turbine, as well as the protection devices have no influence on the continuous operation of the system and they are, thus, not incorporated into the model. In the following sections, the individual model components are described.

Wind simulation: Continuous changes in wind speed are the main reason for power fluctuations in turbine output. The power in the wind is a cubic function of the wind speed and it is important, therefore, to create a correct wind model if realistic results are to be obtained.

Mean wind speed and turbulence intensity are the quantities of interest when analyzing wind from the viewpoint of the power quality impact of a wind turbine on an electric grid. The Turbulence Intensity (TI) is defined as a standard deviation of the wind, WS, over its mean value as follows:

$$TI = \frac{std(WS)}{mean(WS)}$$

The wind becomes turbulent when it passes obstacles in its way. Different terrain profiles contain different kinds of obstacles and the quantity representing this property is a roughness of the surface, Z_0. Some surface examples are the sea, low grass or forest. There is an empirical relationship between the roughness of the surface and turbulence intensity. The roughness of the surface is an important parameter when wind with given turbulence intensity is to be simulated. Figure 5 presents an example of frequency spectra of two measured wind profiles.

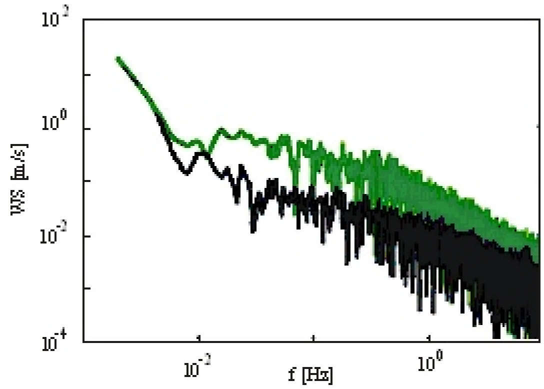

Fig. 5: Frequency spectra of two wind profiles

Wind spectra, black trace - TI = 5 %, gray trace - TI = 20%: Both wind profiles were obtained measuring site with a mean wind speed, in both cases, of 10 m.s^{-1}. The black trace represents wind with Turbulence Intensity (TI) of about 5% (sea wind), while the gray trace represents wind with Turbulence Intensity (TI) of about 20% (land wind).

Single point wind simulation: A method for simulating wind speed at a single point has been presented here. A time series of wind with a given mean speed value and a turbulence intensity can be created. The turbulence intensity is controlled by a choice of the surface roughness and the height of the single point above the surface. An arbitrary sampling frequency of the time series can also be chosen. This approach to simulate wind can be used for developing simple models. An example of a comparison of frequency spectra of measured (black) and simulated (gray) wind series is given in Fig. 6.

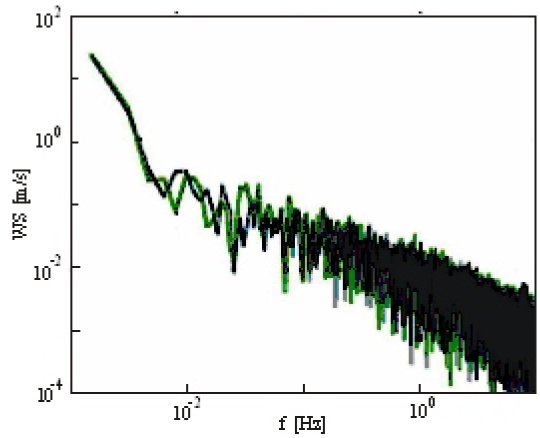

Fig. 6: Frequency spectra of measured and simulated wind series

Wind spectra comparison - single point wind simulation, black - measured, gray - simulated: The mean wind speed is 10 m.s^{-1} and the turbulence intensity here is about 5%. As seen, the agreement between measurement and simulation is very good.

Wind field simulation: When a more detailed model of a wind turbine is to be developed, simulation of the wind at one point is not sufficient. This is because the wind speed over the whole rotor swept area is not constant; different blades and even different blade segments are exposed to slightly different wind speeds. The rotor swept area discretisation is given in Fig. 7.

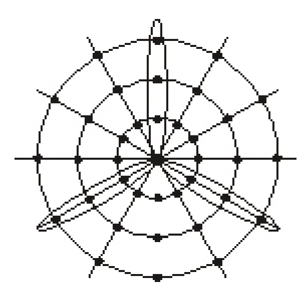

Fig. 7: Rotor swept area discretisation

Wind field discretisation: When simulating wind over the whole rotor swept area, a time series of wind for each node of the discretisation is produced. Knowing the number of blades and the rotational speed of the turbine,

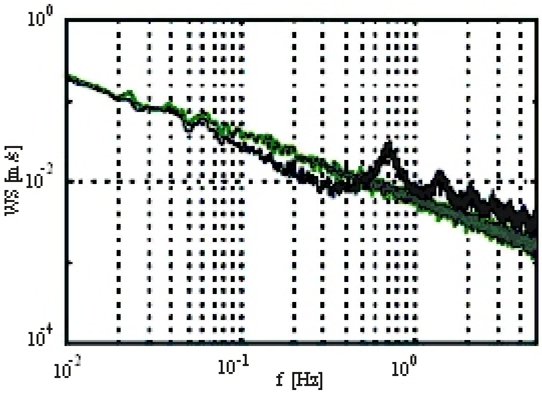

Fig. 8: Spectra of wind at a fixed point and a frequency spectrum of wind acting on a blade segment

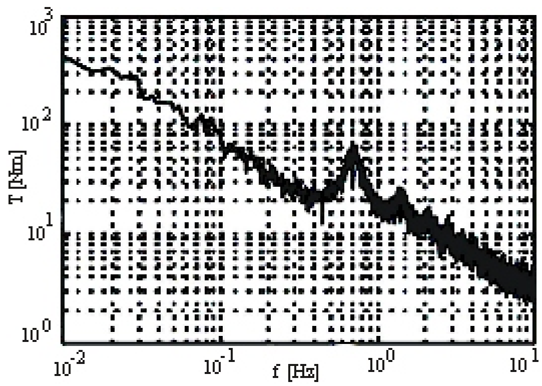

Fig. 9: Spectra of calculated torque on one blade and total shaft torque

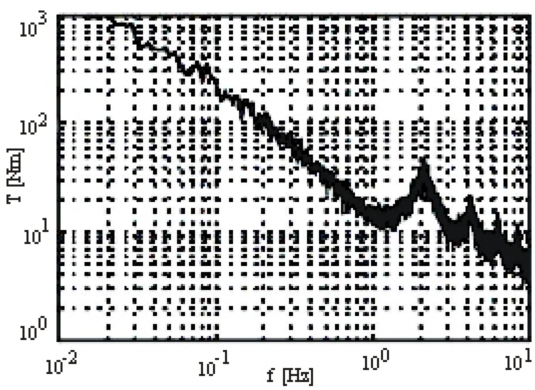

Fig. 10: Frequency spectra of blade torque

a true time series of the wind acting on each individual blade segment can be determined. An example of a comparison of frequency spectra of wind at a fixed point and a frequency spectrum of wind acting on a blade segment is presented in Fig. 8.

Wind spectra comparison - wind field simulation: Gray - wind speed at a fixed point, black - wind speed acting on a blade segment Inspecting the frequency spectra of wind speed acting on an outer blade segment of any chosen blade reveals an important feature. In the frequency band corresponding to the rotational speed of the rotor and its integer multiples, wind speed frequency components are amplified. The data in Figure correspond to a turbine rotational speed of 42 rpm, which gives a frequency of 0.7 Hz. The frequency band amplification around this frequency is apparent. Multiples of this frequency band result in amplification across the whole upper frequency range. The origin of the amplifications mentioned above is the uneven nature of wind speed distribution across the rotor swept area. Wind speed at a single point in the rotor swept area is regularly experienced by the blade. Since wind speed at such a point slightly changes during one rotor revolution, it gives rise to the amplification of the discussed frequency band instead of amplifying only one distinct frequency component. This phenomenon applies to all points in the rotor swept area. Finally, the resulting wind speed acting on a blade is not a sinusoidal function and therefore even multiples of the basic frequency bands can be observed.

Aerodynamic conversion: Knowing the longitudinal component of the wind speed acting on a blade segment, the speed of the blade segment, itself, and the blade pitch angle, the angle of attack can be calculated. Edge and lap forces are then calculated according to the momentum theory and as per the work of Freris. Blade profile aerodynamic data are, of course, a necessary requirement. When the edge forces on all blade segments are known, the torque on each blade and the total shaft torque can be determined. Lateral and vertical wind speed components are also incorporated into determining the forces acting on the blades. It was observed, however, that there is no significant impact on the power quality prediction capability of the overall wind turbine model and, thus, a decision was taken to omit these two wind speed components in the presented model. The mentioned aerodynamic conversion approach does not, however, describe dynamic features of aerodynamic conversion, such as dynamic hysteresis. Provided that the blade pitch angle and the rotor speed are fixed, the torque on a blade segment will be a function of wind speed. Instead of using the momentum theory, an interpolation can be used to calculate torque from wind speed. Both approaches have been used and no detectable difference between obtained results has been found for wind speeds within the operational range of the wind turbine, i.e. 4 to 25 $m.s^{-1}$. The momentum theory is not valid for wind speeds outside this operational range but these wind speeds are not of interest for the wind turbine model presented here. Figure 9 presents spectra of calculated torque on one blade and total shaft torque.

Spectra of a blade torque: The frequency spectra of blade torque given in Fig. 10 exhibits the aforementioned

Table 1: Reonfiguration results with DG and without DG

Network Configuration	Open branches	Losses (kW)Phases A	B	C	Min Voltage (pu) A	Node	B	Node	C	Node
Original configuration	21, 18, 10, 16	73.16	78.76	65.54	0.968	18	0.956	20	0.952	23
Reconfiguration without DG	23, 19, 10, 16	60.19	65.79	52.57	0.978	19	0.965	23	0.964	18
With DG only	23,28,19,11	62.51	68.11	54.89	0.977	28	0.970	11	0.965	26
Reconfiguration with DG (Best)	24, 18, 12, 16	44.26	49.86	36.64	0.987	18	0.984	12	0.984	17

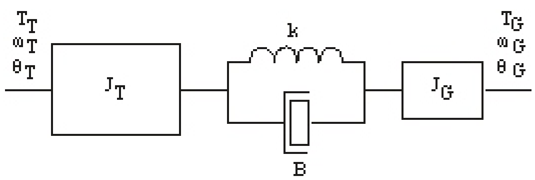

Fig. 11: Drive Train Model

frequency band amplifications. When a three-bladed turbine is used, the observed band amplifications shift to new frequencies, which are three times the values of the original frequencies.

Spectra of a shaft torque:
Drive-train model:
A drive-train model represents the mechanical behavior of the turbine. In a very simplified form, the model consists of turbine and generator inertia and the shaft connecting them, as given in Fig. 11.

Drive-train model:

$$k\Delta v + B\Delta w = J_G \frac{dw_G}{dt} + T_g$$

$$T_T = J_T \frac{dw_T}{dt} + k\Delta v + B\Delta w$$

$$\Delta w = w_T - W_G$$

$$\Delta v = v_T - v_G$$

Where;

T_T, T_G : Torque on the turbine and on the generator shaft, respectively
ω_T, ω_G : Angular speed of the turbine and of the generator shaft, respectively
w_T, w_G : Angle of the turbine and of the generator shaft, respectively
J_T, J_G : Moment of inertia of the turbine and of the generator, respectively
k : Stiffness of the shaft
B : Damping of the shaft

Gearbox inertia is integrated into turbine inertia while gearbox stiffness is added to shaft stiffness. All parameters and quantities are referred to the high-speed end of the gearbox. This model represents the dominant drive-train frequency of the drive train only.

Generator model: A model of a generator is the last part of the overall wind turbine model. Induction machine models of varying complexity have been used here. A standard fifth order model expressed in the d-q coordinate system has been used here as a reference.

$$\overline{u_s} = R_s \overline{i_s} + \frac{d}{dt}[L_s \overline{i_s} + L_m \overline{i_r}]$$

$$0 = R_r \overline{i_r} + \frac{d}{dt}[L_m \overline{i_s} + L_r \overline{i_r}]$$

$$T_G = pp.Im[(L_s \overline{i_s}^* + L_m \overline{i_r}^*)\overline{i_s}$$

$$L_s = L_m + L_{s\lambda}$$

$$L_r = L_m + L_{r\lambda}$$

Where;

u_s :Stator voltage
i_s :Stator current
i_r :Rotor current
T_G :Developed generator torque
R_s :Stator winding resistance
R_r :Rotor winding resistance referred to the stator side
L_m :Generator magnetizing inductance
Ls¸ :Stator leakage inductance
Lr¸ :Rotor leakage inductance referred to the stator side
pp :Number of pole pairs

The simulation results of reconfiguration with DG and without DG are summarized in Table 1 for the example 31 node unbalanced radial distribution system given in Fig. 12. From Table 1, it is evident that the proposed reconfiguration algorithm without DG can improve the voltage profile and reduce power losses. Inclusion of DG further improved the voltage profile of the system and reduced power losses to the minimum, which is given in the best configuration (reconfiguration with wind energy modeled DG)

31 node unbalanced radial distribution system: The 31 node unbalanced radial distribution system in Fig. 12. Composed of five circuits and each circuit are composed of various elements. Circuit 1 comprises of 1, 27, 28, 29, circuit 2 comprises of elements 3, 21, 22, 23, 24, 25, 26, circuit 3 comprises of elements 18, 19, 20, circuit 4 comprises of elements 9, 10, 11, 12, 13,14 and circuit 5 comprises of elements 15,1 6, 17. Elements 5 and 8 are initially open. Starting and ending nodes with impedance of the line are given in Table 2.

Table 2: Details of the system

Element No.	Start node	End node	Impedance
1	31	1	0.13+j0.62
2	1	2	0.17+0.63
3	2	3	0.19+j0.55
4	3	4	0.13+j0.66
5	4	5	0.13+j0.62
6	5	6	0.12+j0.78
7	6	7	0.28+j0.98
8	7	8	0.13+j0.76
9	8	9	0.15+j0.76
10	9	10	0.16+j0.67
11	10	11	0.11+j0.54
12	11	12	0.18+j0.78
13	12	13	0.13+0.77
14	13	14	0.13+j0.76
15	8	16	0.13+j0.55
16	15	16	0.14+j0.56
17	16	17	0.19+j0.67
18	6	18	0.12+j0.65
19	18	19	0.12+j0.65
20	19	20	0.14+j0.76
21	3	21	0.12+j0.66
22	22	23	0.13+j0.65
23	23	24	0.11+j0.97
24	24	25	0.11+j0.97
25	25	26	0.18+j0.95
26	26	27	0.13+j0.54
27	1	28	0.13+j0.65
28	28	29	0.13+j0.67
29	29	30	0.13+j0.56
30	6	21	0.13+j0.65

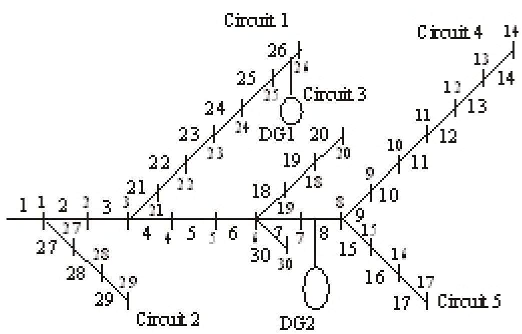

Fig. 12: 31 node Unbalanced Radial Distribution System

Technical data:
Wind turbine data:
Rated power: 180 kW, Hub height: 30 m, Rotor diameter: 23.2 m, Number of blades: 3
Rotor speed: 42 r.min^{-1}, Blade profile: NACA-63200, Gearbox ratio: 23.75.

Drive train data: (All data referred to the high speed shaft) Turbine inertia JT: 102:8 kgm^2, Generator inertia JG: 4:5 kgm^2, Stiffness of the shaft k: 2700Nm rad. Absorption of the shaft B: 1.

Generator data: Nominal voltage Un: 400 V, Number of pole-pairs p: 3, Stator resistance Rs: 0.0092 ohms Rotor resistance Rr: 0.0061 ohms (Referred to the stator) Stator leakage inductance Ls: 186 mH, Rotor leakage inductance Lr: 427 mH (Referred to the stator) Magnetizing inductance Lm: 6.7 mH.

CONCLUSION

Unbalanced radial distribution network reconfiguration in the presence of DGs modeled as wind energy has been investigated in this paper. The 0-1 integer program optimization algorithm has been proposed to obtain optimal system configuration with reduced power losses and optimum power delivered by DG. The impact of wind energy modeled distributed generation on reconfiguration of unbalanced radial distribution system further improves the voltage profile and reduces power losses to the minimum. DG simulation results conclude that by installing neutral clamped inverter, load currents can be balanced at source side and THD of source current can be reduced. To maintain optimum feeder reconfiguration at any point of time, it requires communication between distribution substation, nodes and DG units.

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