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Accurate modeling of doubly fed induction generator based wind farms in load flow analysis

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ABSTRACT

This paper presents an iterative approach for incorporating doubly fed induction generator (DFIG) based variable speed wind farms in steady state studies such as load flow analysis. The proposed approach is based on an accurate steady state equivalent circuit of a DFIG. In the proposed approach, the power flow model of a node with DFIG is determined based on the reference to reactive power control loop of rotor side converter. In addition, the proposed approach takes into consideration various limits associated with the DFIG. Case studies on sample 6-bus system and 418-bus equivalent system of Indian southern grid are presented to validate the proposed approach.

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1. Introduction

The growing demand for power and increased environmental concerns gave an impetus to the growth of clean and renewable energy sources like wind and solar. There is a remarkable increase in the penetration of wind energy systems in the last decade and this trend is bound to increase at a much faster pace in near future. Popular among the class of wind turbine units are the variable speed generators which use Doubly Fed Induction Generator (DFIG) [1]. This paper deals with the modeling of DFIG based wind generators in load flow analysis.

Researchers in the past have reported various methodologies to incorporate wind generators in load flow [2–13]. Initial works focused primarily on modeling of fixed speed wind generators (WGs). In [2,3], the authors propose a PX model for incorporating induction generators in Newton Raphson (NR) approach. In PX model, the active power output is calculated based on the wind speed (presumed to be known) and the magnetizing inductance is incorporated as a shunt element at the node to which the WG is connected.

Another framework that is commonly adopted for incorporating induction generators (fixed speed in particular) is the PQ model [4,5]. In this model, the active power is computed based on the turbine characteristic and the reactive power required is computed using the expressions ($Q = f(P)$) derived based on steady state equivalent circuit. In [4,6], a new framework called the RX modeling is also proposed for incorporating fixed speed wind generators in load flows. A comparison of various methods is reported in [9,10].

With the advancements in power electronic control, variable speed wind generators have become the most preferred choice for use in wind energy conversion systems. As reported in literature, the variable speed wind generators can provide reactive power support to the grid. The most commonly employed models for incorporating DFIG based variable speed wind generators are the PQ and PV models [7,8,11–13].

An approach for modeling variable speed wind generators considering the impacts of various control loops and the associated limits (such as stator and rotor current) is reported in [7]. The approach models the DFIG in *dq* reference frame and is based on an underlying assumption of negligible stator resistance. Further, an approach for calculating the steady state operating conditions of a DFIG based wind turbine without using the *dq* transformation is reported in [8].

Most of the approaches reported in literature are based on the existing steady state equivalent circuit of DFIG. In [14,15], the inconsistency of the existing equivalent circuit of DFIG is reported and subsequently an accurate equivalent circuit is proposed. In addition, some of the approaches presented in the literature do not consider in greater detail, the current limits of the machine

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and the control strategy employed in converters associated with it. In this paper, an accurate power flow model for DFIG based variable speed wind generators is proposed taking these aspects into consideration.

2. Overview of the proposed approach

The method proposed in this paper employs the Newton Raphson (NR) approach for solving the power flow equations [16]. In the NR approach, starting at an initial value (flat start), the non-linear power flow equations are solved in an iterative manner until the convergence criterion is satisfied. The set of non-linear power flow equations can be written in generic form as

$$\begin{aligned} P_i^{spe} - V_i \sum_{j \in i} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] = 0 \\ Q_i^{spe} - V_i \sum_{j \in i} V_j [G_{ij} \sin(\delta_i - \delta_j) + B_{ij} \cos(\delta_i - \delta_j)] = 0 \end{aligned} \tag{1}$$

where $V \angle \delta$ represents the node voltage (in phasor form), G_{ij} and B_{ij} represent the real and imaginary parts of element of the network admittance matrix $[Y_{bus}]$.

For a network with N nodes comprising of g generators, an update to the node voltage (Δx; both magnitude and angle) can be obtained by solving (2).

$$\begin{bmatrix} [\Delta\boldsymbol{\delta}]_{\mathbf{N-1}} \\ [\Delta\mathbf{V}]_{\mathbf{N-g}} \end{bmatrix} = \begin{bmatrix} \left[\dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\delta}}\right] & \left[\dfrac{\partial \mathbf{P}}{\partial \mathbf{V}}\right] \\ \left[\dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\delta}}\right] & \left[\dfrac{\partial \mathbf{Q}}{\partial \mathbf{V}}\right] \end{bmatrix}^{-1} \begin{bmatrix} [\Delta \mathrm{P}] \\ [\Delta \mathrm{Q}] \end{bmatrix} \tag{2}$$

The objective of this paper is to propose a framework for obtaining power flows in networks comprising of DFIG based variable speed wind generators along with the large synchronous generators (SG). The generic framework of the proposed approach is outlined in Algorithm 1.

Algorithm 1. Generic framework of the proposed approach

```
1:  Read the generator and load information (including the
    initial presumed outputs of DFIG)
2:  Initialize the node voltages to flat start (1∠0); k→
    iteration number
3:  while ‖Δx‖ ≤ ϵ do
4:    Solve of Δx using (2).
5:    Update the node voltages, computed values of P and Q at
    various nodes.
6:    Check for reactive power limits of SG.
7:    Check for current limits associated with DFIG.
8:    if any violations in current limits then
9:      Adjust the output of DFIG
10:   end if
11: end while
```

To start with, the DFIG based variable speed wind generators are modeled as PQ or PV buses depending on the control strategy employed in the rotor side converter (RSC). For the chosen model, the network power flow equations are solved till the load flow solution has moderately converged [17] (usually a couple of iterations). Once the solution has moderately converged, the variables corresponding to individual synchronous and wind generators are checked for violation in limits. In the case of synchronous generators, the reactive power output of individual units are examined.

In the case of DFIG based wind generators, the variables to be examined for determining the violations include stator/rotor currents, rotor voltage and mechanical power. It is to be noted that in the case of DFIG, limits must be violated irrespective of whether the corresponding node is modeled as PQ or PV bus. These aspects are discussed in more detail in Section 3.

If any of the violations are encountered, the output of DFIG must be adjusted accordingly. In the subsequent iterations, the specified values at the corresponding buses must be updated according to adjusted settings of the wind generators. In general, the following four important aspects related to DFIG based wind farms must be known apriori to incorporate them in load flow analysis.

1. Type of control employed in converter: The type of control employed in converter (especially RSC) determines whether the bus (corresponding to which the wind generator is connected) must be modeled as PQ bus or PV bus.
2. Mathematical model of DFIG: A steady state model that accurately captures the behavior of DFIG under various operating conditions is very essential. The model must facilitate accurate computation of active and reactive injected by DFIG under all possible operating conditions.
3. Limits of individual machine: The rated values of stator/rotor current, rotor voltage and mechanical power associated with individual machine must be known. Further, it is necessary to establish expressions for computing the adjusted active and reactive power output in case of limit violations.
4. Choice during violations: During violations, the preference i.e. a choice regarding the quantity to be adjusted (i.e. whether to limit the reactive power output (Q) or active power output(P)) must be made apriori.

3. DFIG modeling

The general schematic of a DFIG with associated converters on the rotor side is shown in Fig. 1. The grid side converter (GSC) is generally operated in unity power factor (UPF) mode. The reactive power injected/absorbed via the stator terminals is controlled by the rotor side converter (RSC).

3.1. Choice of bus model

As mentioned earlier, the type of model (i.e. PQ or PV bus) depends on the control strategy employed in the converters. For instance, if vector control in stator flux orientation is employed for RSC, then the block diagram related to reactive power loop is shown in Fig. 1(b). In general, the reference to the outer control loop (shown in Fig. 1(b)) can either be the desired reactive power or the desired stator voltage. If the reference to the outer control loop is the desired reactive power, then the bus to which the DFIG based wind generator is connected is modeled as PQ bus. Analogously, if the reference is chosen as the desired stator voltage, then the corresponding bus is modeled as PV bus.

3.2. Mathematical model of DFIG

3.2.1. Equivalent circuit

The steady state equivalent circuit of DFIG operating at sub and supersynchronous speeds is shown in Fig. 2(a) and (b) respectively.

It is to be noted that the equivalent circuit of DFIG during sub and supersynchronous modes of operation is not the same. The shortcomings of equivalent circuit widely adopted in literature (i.e. Fig. 2(a)) in predicting the reactive power flows during supersynchronous mode of operation is highlighted in [14]. An accurate equivalent circuit is subsequently derived in [14,15]. Contrary to [14,15], the work presented in this paper employs the generator convention (as shown in Fig. 2).

3.2.2. Determination of initial settings

To initiate DFIG based wind turbines in load flow, the active and reactive power output at the terminals must be known in case of PQ modeling. In the case of PV modeling, the active power and the

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