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Small-signal stability analysis of DFIG based wind power system using teaching learning based optimization

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ABSTRACT

The present paper formulates the state space modelling of doubly fed induction generator (DFIG) based wind turbine system for the purpose of small-signal stability analysis. The objective of this study is to discuss the various modes of operation of the DFIG system under different operating conditions such as three phase fault and voltage sags with reference to variable wind speed and grid connection. In the present work, teaching learning based optimization (TLBO) algorithm optimized proportional–integral (PI) controllers are utilized to control the dynamic performance of the modelled DFIG system. For the comparative analysis, TLBO based simulated results are compared to those yielded by particle swarm optimization (PSO) method for the same DFIG model. The simulation results show that the proposed TLBO based PI controller effectively works in minimizing the damping phenomena, oscillation in rotor currents and fluctuation in electromagnetic torque for the studied DFIG model. It is also observed that TLBO is offering better results than the PSO for the dynamic performance analysis of the studied model.

Introduction

In recent years, wind energy has witnessed a large surge in research and development. The drawback of wind energy is that electrical energy is obtained only when the wind blows. Even though modern wind turbines regulate power well and level off at their rated capacity, the amount of power produced by them varies throughout the day. Many installations have established that utility systems are able to accommodate the change in wind generation just as they modify their output to follow dynamic demand. Specialists predict that wind power can constitute up to 30% of present energy demands before reliability of the system would be an issue.

Generation of kinetic energy is done by utilizing the atmospheric air's energy. Wind energy had been used from centuries to perform many different functions such as grain grinding, sailing and for irrigation purposes. The main function of wind power system is conversion of kinetic energy present in the wind into various sources of power. In ancient times, milling and irrigation were also done by wind power systems. During twentieth century, wind power started to generate electricity. Similarly, wind mills were used in several countries to pump water from the ground. Wind turbines can be used as single unit as well as in groups (also known as wind farms). Wind turbines which are smaller in size are also called as aero generators. These can be used for charging large-sized batteries. Five countries in the world has greater than 80% of the installed global wind energy capacity, among them India is at the 5th position [1].

The output power can be improved by 2–6% for a variable speed turbine as compared to a fixed speed turbine [2] whereas it may go up to 39% according to [3]. It is revealed that the energy generation gain of the variable-speed turbine as compared to the fixed-speed turbine may fluctuate by 3–28% according to the condition of site and design consideration [4]. The energy capture is enhanced by 20% in case of doubly fed induction generator (DFIG) when compared to variable speed turbine using a cage bar induction machine and by nearly 60% from fixed speed system. As the assumptions used while performing the study of DFIG varies vastly from one person to another, therefore, the results may also vary accordingly. The controlling of DFIG is far more tedious than controlling any other machine. The rotor current in the DFIG is controlled by power converters. It is controlled by using vector control techniques. Till date, various vector control techniques has been suggested for the controlling of DFIG. The stator flux orientation can be used to control the rotor currents according to the system parameters [5,6]. According to [7,8], the eigenvalues of the DFIG are poorly damped having a corresponding natural frequency close to the line frequency. In addition to this, the DFIG system is not

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Nomenclature

A	state or system matrix
A_1	turbine swept area, m^2
A_{sys}	complete system matrix
B	input matrix
C	output matrix
C_{dc}	DC link capacitance, mF
$c_1 - c_6$	power co-efficients
$C_P(\lambda, \beta)$	performance co-efficient
D	feed forward matrix
D_{tran}	transmission line distance, km
F_b	base frequency, Hz
f_r	rotor frequency, Hz
f_s	supply frequency, Hz
H	total inertia of generator, kg m^2
$i_{dr,ref}$	reference rotor current in direct axis reference, A
$i_{qr,ref}$	reference rotor current in quadrature axis reference, A
I_{ds}	three phase stator current in direct axis reference frame, A
I_{qs}	three phase stator current in quadrature axis reference frame, A
K_{opt}	constant co-efficient
K_{i1}, K_{i2}	integral controller gains
$K_{P1} - K_{P3}$	proportional controller gains
L_m	magnetizing inductance, H
L_{lr}	leakage inductance of rotor winding, H
L_{ls}	leakage inductance of stator winding, H
L_r	self inductance of rotor, H
L_s	self inductance of stator, H
n	synchronous speed, rpm
p	pair of poles
P_m	mechanical output power, W
P_r	rotor power, W
P_s	stator power, W
R_{blade}	blade radius, m
R_e	transmission line resistance, Ohm
R_r	rotor resistance of machine per phase, Ohm
R_s	stator resistance of machine per phase, Ohm
R_T	total resistance, Ohm
s	slip of the machine, p.u.
S_b	base MV A, MV A
T	transpose of matrix
T_{em}	electromagnetic torque, N m
T_m	mechanical torque developed, N m
T_{sp}	set point torque, N m
u	input vector of the model
V_{dc}	DC link voltage, V
v_{dgrid}	grid voltage in direct axis reference frame, V
v_{dr}	three phase rotor voltage in direct axis reference frame, V
$\dot{v}_{dr}$	direct axis rotor voltage signal from PI controller, V
v_{ds}	three phase supply voltage in direct axis reference frame, V
v_{qgrid}	grid voltage in quadrature axis reference frame, V
v_{qr}	three phase rotor voltage in quadrature axis reference frame, V
$\dot{v}_{qr}$	quadrature axis rotor voltage signal from PI controller, V
v_{qs}	three phase supply voltage in quadrature axis reference frame, V
$v_{s,ref}$	stator reference voltage, V
v_w	wind speed, m/s
w_b	base angular frequency, radians per minute
w_r	rotational speed of generator, revolutions per minute
w_s	synchronous angular frequency, radians per minute
$x_1 - x_3$	state vectors
X_e	transmission line reactance, Ohm
X_{ls}	stator leakage reactance, Ohm
X_{lr}	rotor leakage reactance, Ohm
X_m	magnetization reactance, Ohm
X_{rr}	rotor reactance, Ohm
X_{ss}	stator reactance, Ohm
X_T	total reactance, Ohm
X_{TR}	transformer reactance, Ohm
y	output vector of the model
β	blade pitch angle, deg
λ	tip speed ratio, p.u.
ρ	air density, kg/m^3
ψ_{dr}	rotor flux in direct axis reference frame, Wb
ψ_{ds}	stator flux in direct axis reference frame, Wb
ψ_{qr}	rotor flux in quadrature axis frame, Wb
ψ_{qs}	stator flux in quadrature axis reference frame, Wb
$\dot{x}_1 - \dot{x}_3$	first derivative of $x_1 - x_3$

stable for various operating conditions. The poorly damped poles of the DFIG affect the dynamics of rotor current from the back electromotive force. The response of wind turbines to grid disturbances is a crucial issue, particularly, since the rated power of wind-turbine installations will increase slowly. Therefore, it is vital for utilities to be capable to study the results of several voltage sags and also the resultant turbine response. It is desirable to have a simple model that is able to model the dynamics of concern. In [9–11], a third-order model has been planned that neglects the stator-flux dynamics of the DFIG. This model provides an accurate mean value [9]. However, a disadvantage is that some of the crucial dynamics of the DFIG system are also neglected. So, as to preserve the dynamic behaviour of the DFIG system, a rather totally different modelling approach should be followed. As discussed previously in the literature, a dominating feature of the DFIG system is that the natural frequency of the flux dynamics is near the line frequency. Since the dynamics of the DFIG are influenced by two poorly damped eigenvalues (poles), it might be natural to condense the model of the DFIG to the flux dynamics described by a second-order model. This is one typical way to scale back model of DFIG in typical control system stability analysis [8]. The chance of its usage as a simulation model is yet to be shown, so as to preserve the behaviour of the oscillatory response. It is clear that second-order simulation model is the easiest one to use. At present, the DFIG wind turbine is disconnected from the grid when huge voltage sag appears in the system. When wind turbine is disconnected from the system, it needs few seconds before it can be reconnected with the system. This means that the wind turbine needs to have extra protection to avoid these voltage dips. Today's DFIG system encompasses a crowbar within the rotor circuit that at large grid disturbances must short circuit the rotor so as to shield the converter. This highlights that the turbine should be separated out from the grid, if large voltage sag occurs.

According to the works reported earlier, there are different ways to change the DFIG system so that it can withstand the voltage sags. In [12], thyristors are placed in anti-parallel topology within the stator so as to achieve fast (less than 10 ms) discontinuation of the stator and, thus, enabling it to re-magnetize the turbine generator as well as rejoin the stator from the grid as quickly as possible. The technique, proposed in [13], uses an "active" crowbar which disintegrates the short circuit current to a minimum value. All of these systems have completely different dynamic