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A power control strategy to improve power system stability in the presence of wind farms using FACTS devices and predictive control

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ABSTRACT

The main objective of this paper that distinguishes it from other similar articles is to employ predictive control strategy to improve the stability of power systems (4- machines and 10-machine) in presence of wind farms based on Doubly Fed Induction Generator (DFIG), using Static Synchronous Series Compensator (SSSC) and Super Capacitor Energy Storage System (SCESS). In this paper, SCESS is used to control the active power in the Grid Side Convertor (GSC) and SSSC is employed to reduce low frequency oscillations. The proposed strategy based on the predictive control can be simultaneously used to control the active and reactive power of the Rotor Side Convertor (RSC) as well as damping controller design for SCESS and SSSC. A function is used in the predictive control strategy to reduce computational complexity in selecting the input paths of Laguerre functions. Moreover, the sampling time is reduced by means of employing the exponential data weighting. Simulation results for the function-based predictive control using disturbance scenario in the field of non-linear time are compared with the other two methods, model-based predictive control and classic model (without using the predictive control). The effectiveness of the proposed strategy in improving stability is confirmed through simulation result.

1. Introduction

1.1. Motivation and approach

Due to world population growth today, diminishing fossil fuels sources and concerns about environmental pollution, the use of renewable energy resources has drawn more and more attention of researchers. Among the renewable energy sources, wind energy is one of the most popular type of energy to produce electricity throughout the world. But because of the fluctuating nature of wind power, the use of this energy causes the electricity produced by wind farms to be oscillated in electrical grids. Hence, the existence of such fluctuations from the stability and power quality point of view is non-negligible in a power system [1,2]. This can be considered in all types of variable and constant speed wind turbines. In this regard, the use of Energy Storage System (ESS) and Flexible AC Transmission Systems (FACTS) devices can be very useful as a compensator to reduce oscillations and increase damping in power systems [3,4]. Extensive studies have been done in the field of power system stability in the presence of wind farms and compensator devices. However, finding a method that can lead to the development of industry and technology requires previous studies and employing their advantages and disadvantages. Therefore, in this paper that its main objective is to use the predictive control strategy to improve the stability of a hybrid power system including wind farms, synchronous generators, energy storage systems and FACTS devices, the most recent studies in each field are needed to be evaluated.

1.2. Review of previous publications

Due to low-cost and direct control of active and reactive power, doubly fed induction generator is considered as one of the most common types of variable speed wind turbine [5]. The rotor of this generator is connected to the grid through a back-to-back bi-directional converter and its stator is connected directly to the grid. A three loop controller including GSC, RSC and a control loop for DC link capacitor for connecting these two converters is used to control the bi-directional converter. Several studies have been made in recent years to stabilize the DFIG control systems, some of which include sensitivity analysis [6], small signal stability analysis [6–8], eigenvalues analysis [9], approaches based on optimizing control parameters in each of DFIG converters [10–12], a state feedback [13] and robust control $H2/H\infty$ [14]. In the optimization-based methods, the parameters of PI controller in

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Nomenclature

$P_{\omega t}$	extracted power from the wind turbine (W)
$\rho_{\omega t}$	air density (kg/m^3)
$K_{\omega t}$	swept area of blades (m^2)
$V_{\omega t}$	wind speed (m/s);
$D_{\omega t}$	performance coefficient of blades
$\beta_{\omega t}$	blade pitch angle
$\lambda_{\omega t}$	tip speed ratio
$d_1 - d_9$	constants
R_b	blade radius (m)
ω_b	angular velocity of blade (rad/s)
L_{ss}	self-inductance of stator
L_{rr}	self-inductance of rotor
L_{mm}	mutual inductance
R_s	stator resistance
R_r	rotor resistance
i_{ds}	stator current in d-axis
i_{qs}	stator current in q-axis
i_{dr}	rotor current in d-axis
v_{ds}	rotor current in q-axis
v_{dr}	stator voltage in d-axis
v_{qs}	stator voltage in q-axis
v_{dr}	rotor voltage in d-axis
v_{qr}	rotor voltage in q-axis
H_t	inertia constant of wind turbine
H_g	inertia constant of generator
ω_t	angular speed of wind turbine
ω_r	angular speed of rotor of generator
$T_{\omega t}$	mechanical torque of wind turbine
T_{tg}	shaft torque
$T_{e\omega t}$	electrical torque of wind turbine
K_t	damping coefficient of turbine
K_g	damping coefficient of generator
K_{tg}	inertia constant of wind turbine
L_{tg}	inertia constant of generator
P_{dc}	active power of the DC link
P_{rw}	active power of the rotor-side converter
P_{gw}	active power of the grid-side converter
C_{dc}	capacity of the DC link capacitor
V_{dc}	voltage of the DC link capacitor
Z_{q1} & Z_{i1}	PI controller coefficients for regulating the reactive power
Z_{q2} & Z_{i2}	voltage of the DC link capacitor
Z_{q3} & Z_{i3}	PI controller coefficients for regulating the reactive power
i_{drw_ref}	current control in d-axis for RSC
i_{qrw_ref}	current control in q-axis for RSC
Q_{sw_ref}	reference reactive power
ω_{rw_ref}	reference speed
Z_{bg} & Z_{ig}	coefficients of the PI controller for regulating the voltage of DC link capacitor
Z_{pb} & Z_{pi}	coefficients of the PI controller for regulating the current of GSC
i_{qgw_ref}	reference current control in q-axis for GSC
V_{dc_ref}	reference voltage of the DC link capacitor
$Z_{b\beta}$ & $Z_{i\beta}$	coefficients of the PI controller
$\tau_{b\beta}$	delay time constant for blade pitch angle control
P_{gw}	power of wind turbine measured for the blade pitch control
P_{gw_ref}	reference power of wind turbine for the blade pitch control
$x(k)$	state vector of MPC
$u(k)$	input vector of MPC
$e(k)$	disturbance vector of MPC
$y(k)$	output vector of MPC
k	sampling instant
G_k	weighting matrix of the cost function
S_k	weighting matrix of control action in the cost function
$y'(n+k)$	prediction vector of the output signal
$y_{ref}(n+k)$	reference path of system's future
$\Delta u(n+k)$	action control vector
m_c	turns ratio of the coupling transformer of SSSC
Z_{inv}	modulation index of SSSC
V_{dc_sssc}	DC capacitor voltage of SSSC
β_s	phase angle of the injected voltage of SSSC

each of the induction generator converters are optimized by intelligent algorithms to apply the output of the controller with the lowest error to the relevant converter. PI controllers core problem is their dependence on operating point as well as their sensitivity to change in system conditions. Hence, the neural network and fuzzy logic based algorithms have been used in some studies to solve this problem which have their own complexity and disadvantages as well [15,16]. Another method for reducing oscillations of the DFIG output power is to use Super Capacitor Energy Storage System [17,18]. Given that the use of power electronic devises is reduced in energy storage systems, in addition to reducing the cost in case of designing a proper controller, an output power with the lowest oscillation will be achieved by DFIG [19]. In these systems, if the wind turbine undergoes oscillations as a result of drastic change in wind, the power required by the system can be easily compensated through a DC-DC converter [20]. In addition, Flywheel Energy Storage System (FESS) [21,22], and Superconducting Magnetic Energy Storage (SMES) can be noted as other energy storage systems used at AC bus to compensate reactive power [23–25]. One of the methods to reduce low frequency oscillation (LFO) in the power system stability studies is to design damping controller for power system stabilizer (PSS) or FACTS devices. The SSSC is a new generation of FACTS devices which is connected in series with transmission lines and leads the power flowing in transmission lines to be converted from capacitive to inductive [26,27]. Therefore, the regional and inter-regional oscillations can be mitigated through a proper controller design for SSSC and PSS. Different methods have been proposed to design a suitable controller for SSSC [28–33]. Wavelet neural adaptive method to design PID controller [28], nonlinear robust control method to improve damping and transient stability [29], methods based on intelligent algorithms to optimize lead-lag controller parameters in the design of coordinated PSS-SSSC [30,31], damping controller design for SSSC in the presence of wind farms using adaptive-network-based fuzzy inference system (ANFIS) considering time delay [32] and modal analysis [33] are some of the approaches to increase stability of power systems using this type of FACTS devices. The above-mentioned techniques are able to provide a desired response to system in case of the detailed design. But in case of multiple disturbances in a power system and lack of certainty in a wind system, a method is required to guarantee stability under all conditions. In other words, this method should be able to apply the constraints of the system as well as simultaneously control of multiple parameters with the lowest output error so as to ensure the stability of the system. The predictive control is presented as a very powerful control tool for meeting the above requirements. Model Predictive Control (MPC) is assumed as one of the advanced control methods in the field of industrial operations and research