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Recurrent modified Elman neural network control of PM synchronous generator system using wind turbine emulator of PM synchronous servo motor drive

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A R T I C L E I N F O

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A B S T R A C T

The recurrent modified Elman neural network (NN) controlled a permanent magnet (PM) synchronous generator system, which is driven by wind turbine emulator of a PM synchronous motor servo drive, is developed to regulate output voltage of rectifier (or AC to DC power converter) and inverter (or DC to AC power converter) in this study. First, the wind turbine emulator of a closed loop PM synchronous motor servo drive is designed to produce the maximum power for the PM synchronous generator system. Then, the rotor speed of the PM synchronous generator, the output DC bus voltage and current of the rectifier are detected simultaneously to yield maximum power output of the rectifier through DC bus power control. Because the PM synchronous generator system is a nonlinear and time varying dynamic system, the online training recurrent modified Elman NN control system is developed to regulate DC bus voltage of the rectifier and AC line voltage of the inverter in order to improve the control performance. Furthermore, the online training recurrent modified Elman NN control system with the variable learning rate is derived based on Lyapunov stability theorem, so that the stability of the system can be guaranteed. Finally, some experimental results are verified to show the effectiveness of the proposed recurrent modified Elman NN controlled PM synchronous generator system.

1. Introduction

Since the petroleum gradually exhausting and environmental protection progressively rising, the usage of the clean energy sources has become very importance in the electric power applications. Clean energy sources such as wind, photovoltaic, and fuel cells can be interfaced to a multilevel converter system for a high power application [1–3].

Wind turbine acted as sources of energy has progressively increased in the whole earth. A few control methods and conversion technologies in wind energy application are developed in the wind energy conversion systems. The PM synchronous generator system has been used for wind power generating system due to many advantages such as simpler structure, better reliability, lower maintenance and higher efficiency [4–8]. Therefore, the PM synchronous generator generation system stands for a significant trend in progress of wind power applications [4–8]. The output power behavior of wind turbine is nonlinear. The provided power of vertical-axis turbines is very sensitive to the load variation due to different structure effect [4–8]. Thus, the control of operating point is indispensable for maximum output power. The controllable rectifier is used to convert varied AC voltage generated by PM synchronous generator into DC bus voltage. Then, the controllable inverter is used to convert DC bus voltage into AC at a fixed frequency in order to provide for the stand alone or grid applications of electrical utilizations. The major purposes utilized wind turbines are to extract maximum power of turbine and deliver appropriate energy to stand alone power or grid power. According to these purposes, the better structure of the power conversion in wind turbines is the AC to DC to AC power converter [9,10].

Over the past decade, many different control approaches were used to generator and wind turbine emulator for energy generation [11–18]. In [11,12], a fuzzy logic control is adopted to control the power of the wind electrical conversion system transmitted to the grid and generator speed. The advantage in using fuzzy logic controller against standard proportional-integral (PI) controller, is pointed out in better response to frequently changes in wind speed. In [13], the rule-based fuzzy-logic based maximum power point tracking (MPPT) strategy is proposed for PM synchronous generator variable speed wind turbine generation systems. The fuzzy-logic-based output power smoothing method of a wind energy conversion system (WECS) with a PM synchronous generator using the inertia of wind turbine was proposed in [14]. In [15], a sliding mode control (SMC) strategy associated to the field-ori-

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Nomenclature

v_{d1}, v_{q1}	d-axis and q-axis stator voltages of the PM synchronous generator
i_{d1}, i_{q1}	d-axis and q-axis stator currents of the PM synchronous generator
L_{d1}, L_{q1}	d-axis and q-axis inductances of the PM synchronous generator
R_{s1}	phase winding resistance of the PM synchronous generator
ω_{r1}, n_{r1}	rotor angular velocity of the PM synchronous generator in rad/s, in rpm
λ_{pm}	permanent magnet mutual flux linkage of the PM synchronous generator
P	number of poles of the PM synchronous generator
β	tip ratio of the wind turbine
R_1	turbine rotor radius of the wind turbine
T_1	output torque of the wind turbine
T_e	electromagnetic torque of the PM synchronous generator
J_1	moment of inertia of the PM synchronous generator
B_1	viscous friction coefficient of the PM synchronous generator
ρ_1	density of air
K_t	torque constant of the PM synchronous generator
A_1	exposed area of the wind turbine
$D_p(\beta)$	coefficient of power performance
P_1	output mechanical power of the wind turbine
v_1	wind speed
θ_{r1}	rotor position of the PM synchronous generator
θ_{i1}	electric angular angle of the inverter
i^*_{dr}, i^*_{qr}	d-axis and q-axis control currents of the rectifier
i^*_{ar}, i^*_{br}, i^*_{cr}	desired phase currents of the PM synchronous generator in phases ar, br and cr
i_{ar}, i_{br}, i_{cr}	measured phase currents of the PM synchronous generator in phases ar, br and cr
T_{ar}, T_{br}, T_{cr}	sinusoidal pulse-width-modulation control signals of the rectifier in phases ar, br and cr
V_d, V^*_d	measured magnitude of the DC bus voltage of the rectifier, desired magnitude of the DC bus voltage of the rectifier
i^*_{di}, i^*_{qi}	d-axis and q-axis control currents of the inverter
i^*_{ai}, i^*_{bi}, i^*_{ci}	desired phase currents of the inverter in phases ai, bi and ci
i_{ai}, i_{bi}, i_{ci}	measured phase currents of the inverter in phases ai, bi and ci
T_{ai}, T_{bi}, T_{ci}	sinusoidal pulse-width-modulation control signals of the inverter in phases ai, bi and ci
V_{rms}, V^*_{rms}	measured root-mean-square magnitude of the AC 60 Hz line voltage of the inverter, desired root-mean-square magnitude of the AC 60 Hz line voltage of the inverter
$c^1_{i,m}$, $c^2_{i,m}$, $c^3_{j,m,}$, $c^4_{k,m}$	inputs of nodes i in the input layer, the hidden layer, the context layer and the output layer of the mth recurrent modified Elman NN
$g^1_{i,m}$, $g^2_{j,m}$, $g^3_{k,m}$, $g^4_{o,m}$	activation functions in the input layer, the hidden layer, the context layer and the output layer of the mth recurrent modified Elman NN
$node^1_{i,m}$, $node^2_{j,m}$, $node^3_{k,m}$, $node^4_{o,m}$	node functions in the input layer, the hidden layer, the context layer and the output layer of the mth recurrent modified Elman NN
$d^1_{i,m}$, $d^2_{j,m,}$, $d^3_{k,m}$, $d^4_{o,m}$	output of nodes in the input layer, the hidden layer, the context layer and the output layer of the mth recurrent modified Elman NN
N	number of iterations
l_1	total number of node in hidden layer
n	total number of node in context layer
α_m	self-connecting feedback gain of context layer in the mth recurrent modified Elman NN
$\mu^2_{ij,m}$	connective weights between input wavelet layer (i layer) and hidden layer (j layer) in the mth recurrent modified Elman NN
$\mu^3_{kj,m}$	connective weights between context wavelet layer (k layer) and hidden layer (j layer) in the mth recurrent modified Elman NN
$\mu^4_{jo,m}$	connective weights between hidden layer (j layer) and output layer (o layer) in the mth recurrent modified Elman NN
$\mu^1_{oi,m}$	recurrent weights between output layer (o layer) and input layer (i layer) in the mth recurrent modified Elman NN
$d^4_{o,1} = U_{R1}$, $d^4_{o,2} = U_{R2}$	output of the output layer in the first mth recurrent modified Elman NN, output of the output layer in the second recurrent modified Elman NN
ψ_m	collections vector of the adjustable parameters in mth recurrent modified Elman NN
$\boldsymbol{\chi}_m$	inputs vector of the output layer in the mth recurrent modified Elman NN
γ_m, γ^*_m	learning rates in the mth recurrent modified Elman NN, optimal learning rates in the mth recurrent modified Elman NN
$V_{c,m}$,	cost function in the mth recurrent modified Elman NN
$\Delta\mu^4_{kj,m}$	change of connective weights between context layer (k layer) and hidden layer (j layer) in the mth recurrent modified Elman NN
$\rho_{j,m}$	error term in the mth recurrent modified Elman NN
$L_{2,m}$	discrete-type Lyapunov function in the mth recurrent modified Elman NN
$P_{j,m} \equiv \partial d^2_{j,m}/\partial u^3_{kj,m}$	partial differentiation with respective to connective weights between the context layer and the hidden layer in the mth recurrent modified Elman NN
$Q_{j,m} \equiv \partial d^2_{j,m}/\partial u^2_{ij,m}$	partial differentiation with respective to connective weights between the input layer and the hidden layer in the mth recurrent modified Elman NN
$R_{j,m} \equiv \partial d^2_{j,m}/u^1_{oi,m}$	partial differentiation with respective to recurrent weights between the output layer and the input layer in the mth recurrent modified Elman NN
$u^*_{rm,m}$	ideal neural controller
ε_m	minimum approximation error
$F_m(s)$	error function of the control effort for the rectifier and the inverter
δ_m	approximation error bound
z_m	error tracking index
$L_{1,m}$	Lyapunov function
δ_m	uncertain bound
$\hat{\delta}_m$	estimation value of uncertain bound
$\tilde{\delta}_m$	estimation error of uncertain bound
k_{p1}, k_{p2}	the constants of the output voltage for rectifier and inverter
V_{abr}	the line-line output voltage of the PM synchronous generator
ζ_1, ζ_2	the regulated values of the output voltage for rectifier and inverter
$\Delta\zeta_m$	control effort of control system for rectifier and inverter
$u_{rmc,m}$	recurrent modified Elman NN control system for rectifier and inverter
$u_{rm,m}$	recurrent modified Elman NN controller for rectifier and inverter
$u_{c,m}$	compensated controller for rectifier and the inverter
$\Vert\cdot\Vert$	the Euclidean norm in $\Re^n$