Performance Comparison of Reactive Power Controllers in Autonomous Wind-Diesel System

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Abstract

This paper presents an automatic reactive power control of autonomous wind-diesel hybrid power systems (AWDHPS) by artificial neural network (ANN) controller tuned static var compensator (SVC). The real time assessment of such control was carried out using dSPACE R & D controller board. The proposed ANN controller was supported by multilayer perceptron artificial neural network (MPANN). The weights of proposed MPANN were restructured by intensive learning process. The back propagation equations were used to dynamically regulate the weights of proposed MPANN controller. Three models of AWDHPS were considered in the study. The disturbance parameters in the models were the change in reactive power of the load (ΔQL), the change in mechanical power input of the single induction generator (ΔPIW) and the change in mechanical power input of two induction generators ($\Delta PIW1$, $\Delta PIW2$) respectively. The parameters were dynamically varied in control desk of dSPACE Software with DS1104 R & D controller board mounted in personal computer under real time environment. The static and dynamic response curves were depicted. The reactive power deviations realized using the proposed MPANN controller was found to be very less compared to the deviations shown in ANN controller present in literature. The time domain

specifications of SVC obtained by the proposed MPANN controller were better than a Proportional plus Integral (PI) controller.

Keywords: dSPACE, Neural Networks, Reactive Power Control, Wind-Diesel System.

1 Introduction

The AWDHPS is becoming a viable and cost effective approach for remotely located communities [1]. In AWDHPS the wind energy system is the main constituent and diesel system forms the back up. The output of wind energy system with induction generator and diesel system with synchronous generator are connected to a common bus. The isolated loads not having access to main grid are connected to this common bus. This type of hybrid power system saves fuel cost, improves power capacity to meet the increasing demand and maintains the continuity of supply in the system [2]. The reactive power control of AWDHPS is based on the mathematical modeling of the system using power equations. The components of AWDHPS such as induction generator, synchronous generator, IEEE type – I excitation system and SVC are modelled individually to achieve their transfer functions. Then these transfer function blocks are combined together to build the MATLAB/Simulink model of the AWDHPS. These models of the AWDHPS were developed to perform the reactive power control under constant speed, variable speed and multi-wind diesel operations [3]. The SVCs are used to control the reactive power [4, 5].

The important characteristic of an ANN is its ability to solve an intricate problem very efficiently. Since the knowledge related to the problem is spread in the neurons and the connection weights of links between neurons the information are processed in parallel. The ANN has been applied to many power system problems [6, 7] and this shows that the ANNs have a great potential in power system applications. The ANN has been applied to tune the SVC over a wide range of load models [8]. The ANN play vital role in energy systems [9]. A 11 kW variable speed wind turbine control model is developed using MATLAB/Simulink and tested with dSPACE DS 1103 [10].

This paper presents the automatic reactive power control of AWDHPS by tuning SVC using the proposed MPANN. The MATLAB/simulink models of three different AWDHPS were built by integrating MPANN as the controller for tuning the SVC. The MPANN controller is illustrated with the input and back propagation equations and flowchart of algorithm. The performance of proposed MPANN controller was established by dynamical variation of the

above disturbance parameters. Then MATLAB/simulink models of AWDHPS were built and assessed in dSPACE real time environment. The results such as reactive power deviations and time domain specifications were tabulated and discussed. The dSPACE real time response graphs of AWDHPS models are presented.

2 AWDHPS Models Investigated

The AWDHPS has been classified into three models based on the disturbance variables of the system.

AWDHPS Model – I: It is a Static Response Model (one variable). It is subjected to variation of change in reactive power of the load (ΔQ_L) alone.

AWDHPS Model – II: It is a Dynamic Response Model (two variables). It is subjected to variation of ΔQ_L and change in mechanical power input of single induction generator (ΔP_{IW}).

AWDHPS Model – III: It is a Dynamic Response Model (three variables). It has two wind system and one diesel system. It is subjected to variation of ΔQ_L and change in mechanical power input of two induction generators (ΔP_{IW1} , ΔP_{IW2}).

The equations governing the reactive power control of AWDHPS are given below [3]. The change in system voltage due to reactive power disturbances of the AWDHPS is given by

$$\Delta V(s) = \frac{K_V}{1 + sT_V} [\Delta Q_{SG}(s) + \Delta Q_{SVC}(s) - \Delta Q_L(s) - \Delta Q_{IG}(s)] \quad (1)$$

where ΔQ_{SG} is change in reactive power generated by SG (pu kVAR); ΔQ_{SVC} is change in reactive power generated by SVC (pu kVAR); ΔQ_L is change in reactive-power-load demand (pu kVAR); ΔQ_{IG} is change in reactive power required by IG generator (pu kVAR); K_V is AWDHPS gain constant; T_V is AWDHPS time constant in seconds.

The change in reactive power of the synchronous generator, induction generator and SVC are given by the Equations (2), (3) and (4) respectively.

$$\Delta Q_{SG}(s) = K_3 \Delta E'_q(s) + K_4 \Delta V(s) \quad (2)$$

$$\Delta Q_{IG}(s) = K_7 \Delta V(s) + K_6 \Delta P_{IW}(s) \quad (3)$$

$$\Delta Q_{SVC}(s) = K_8 \Delta V(s) + K_9 \Delta B_{SVC}(s) \quad (4)$$

AWDHPS Models are given in the Appendix A and B respectively. Then the MATLAB/simulink models of AWDHPS were built in dSPACE real time environment. The disturbance parameters (ΔQL , ΔPIW , $\Delta PIW1$ and $\Delta PIW2$) are dynamically varied in control desk of dSPACE Software with DS1104 R & D controller board mounted in personal computer under real time environment. The individual performance of proposed MPANN controller and PI controller in the above real time environment were recorded.

3 MPANN Controller for Tuning of SVC

The proposed multilayer perceptron artificial neural network (MPANN) controller consists of only one neuron in each layer and undergoes intensive learning for updating the weights. The non-linearity is imposed in the hidden layer alone by the log-sigmoid transfer function. The log-sigmoid function is taken because its output always lies between 0 and 1.

Hence the control signal also lies between 0 and 1. As a result the output from hidden neurons is 0.5 when the input to the proposed MPANN is zero. The output from the hidden neurons with the output layer weights is established as a result of iteration. The output provides a control signal to make the steady state error as zero. The input and back propagation equations governing the MPANN controller are given below.

The change in system voltage and the change in reactive power load demand are the input (IC) to the proposed MPANN controller. It is given by Equation (6)

$$IC = \Delta V + \Delta QL \quad (6)$$

The input (I) to the neurons of the hidden layer is given by following equation

$$I = IC \times W1 \quad (7)$$

The output (OH) from the hidden layer after passing into log-sigmoid transfer function is

$$OH = 1/(1 + e^{-I}) \quad (8)$$

The control signal (CS) from the output layer is determined by

$$CS = OH \times W1 \quad (9)$$

The weights (ΔW_1) of the hidden layer are restructured by Equation (10)

$$\Delta W_1 = (-1) \times \gamma \times \Delta 1 + (\theta \times \Delta W_1(\text{PREV})) \quad (10)$$

where $\Delta 1$ is derivative of the output of the hidden layer; γ is learning rate; θ is momentum constant.

The weights (ΔW_2) of the output layer are restructured by Equation (11)

$$\Delta W_2 = (-1) \times \beta \times OH + (\theta \times \Delta W_2(\text{PREV})) \quad (11)$$

where β is learning rate.

In AWDHPS Model –I, II and III the values of γ , β and θ are 0.6, 0.0001 and -1 respectively. These values were achieved through trial and error method.

The derivative ($\Delta 1$) of the output of the hidden layer with regard to its associated input weights is

$$\Delta 1 = OH \times (1 - OH) \times IC \quad (12)$$

The flow chart of the algorithm is shown in Figure 2. The momentum constant, the learning rate of hidden layer and output layer are observed at first and

Figure 2 Flowchart of MPANN Control Process.

the weights are initialized accordingly. The change in system voltage and change in reactive power load are obtained from AWDHPS. The input/output parameters of the hidden layer are calculated using the Equations (7), (8) and (9). The control signal is given to SVC for initiating reactive power control of AWDHPS. Depending upon the change in load and reactive power the weights of hidden layer and output layer are restructured using the Equations (10), (11) and (12).

4 AWDHPS in dSPACE Environment

The dSPACE system consists of three components: the DS1104 controller board mounted within a personal computer, a breakout panel for connecting signal lines to the DS 1104 controller board and software tools for operating the DS1104 controller board through the Simulink environment. The Real Time Interface data of AWDHPS Model – III is shown in Figure 3. Initially

Figure 3 Real Time Interface Data of AWDHPS Model – III.

the AWDHPS models with MPANN controller were prepared in Simulink as shown in Figure 1. The MPANN controller based Simulink models were built one by one in the Control Desk Software. During each build process, Matlab converts Simulink model into system description file (sdf). The sdf file consists of the code downloaded to the DS1104 Processor. The sdf file is used by dSPACE Control Desk to map the variables of the Simulink diagram to the variables displayed or controlled in the layout. After the building process, sdf file is transferred to control desk environment automatically. This file contains information of variables used in simulink model. These variables can be directly plotted using control desk software environment. Then a new layout file was started in control desk and the capture setting block from instrument panel was selected. The layout screen was drawn. Similarly a plotter array was selected. An appropriate variable was selected from down menu and dropped into the plotter block. Finally the animation mode was started and the variation of variables was observed on the plotter array. The information was saved in mat file version using capture setting window.

5 Reactive Power Deviations

The simulink models used in the study are referred from [3]. The parameters used are given in Appendix A and B. The three AWDHPS Models are implemented as per the discussion given in Section 4. Even though the time span of entire analysis is large it is possible to observe the performance curve variations within a time span of 0.01 sec using the dSPACE environment. Hence a clear visual representation of the performance curves for smaller time span (0.01 sec.) is depicted in Figures 4 (a to e), 5 (a to e) and 6 (a to e). The static and dynamic real time response curves of AWDHPS Models – I, II and III obtained by proposed MPANN for a wide variation of the disturbance parameters (ΔQL , ΔPIW , $\Delta PIW1$ and $\Delta PIW2$) are shown in Figures 4, 5 and 6 respectively. In [3], the maximum deviations of various parameters (ΔV , ΔQSG , $\Delta QSVC$ and ΔQIG) obtained through ANN in MATLAB/simulink environment are given for AWDHPS Models – II and III (with ηq values 3.25 and 1.25) only and not for AWDHPS Model – I. The maximum deviations of the parameters of AWDHPS Models – II and III obtained by the proposed MPANN controller in dSPACE environment for the same values of ηq were compared with [3] in Tables 1 and 2 respectively in order to establish its performance. The change in system voltage (ΔV) is significantly reduced by the proposed MPANN controller.

4(a)

4(b)

4(c)

Figure 4 (a to e). Real time responses of the AWDHPS Model – I obtained by MPANN.

6 Time Domain Specifications

6.1 Performance of MPANN in AWDHPS Model – I

The reactive power load change is a disturbance parameter in the AWDHPS Model – I (It is assumed as a step block). The reactive power load change is compensated by the components such as SVC and SG in the model as given in Equation (1). The reactive power load change is varied from 0.01 to 0.04 p.u. using the knob. The performance curves of various components such as SVC, SG and IG are shown in Figure 4 (a to e). The advantage of real time study is

5(a)

5(b)

5(c)

5(d)

5(e)

Figure 5 (a to e). Real time responses of the AWDHPS Model – II obtained by MPANN.

that reactive power load change is varied from 0.01 to 0.04 p.u. with a time span of 0.85 sec to 1.8 sec and it is visually shown in the Figure 4 (a to e). It is found that the reactive power is supported fully by SVC for the reactive power change whereas the reactive power variations in SG and IG are very less. The performance of voltage variation under step change in load is also an important parameter considered in the study. Hence the time domain response specifications such as percent over shoot, settling time, rise time, peak time and steady state value of SVC for reactive power load changes from 0.01 to 0.1 p.u. were observed. The time domain specifications of SVC obtained by the proposed MPANN controller was compared with a PI controller and

tabulated in Table 3. It is observed that as the load change occurs from 0.01 to 0.1 p.u. the settling time is reduced at a faster rate by MPANN controller to damp the oscillations. The percentage peak overshoot is very less. Thus the performance of proposed MPANN controller is found to be good.

6(a)

6(b)

Figure 6 (a to e). Real time responses of the AWDHPS Model – III obtained by MPANN.

Table 1 Comparison of maximum deviations of parameters of AWDHPS Model – II

Parameter of Model – II	Type of Controller	For $\eta q = 3.25$ and ΔQL (p.u.) = 0.031	For $\eta q = 1.25$ and ΔQL (p.u.) = 0.029
ΔV (p.u.)	ANN [3]	-0.001900	-0.001564
	Proposed MPANN	-0.000160	-0.000148
ΔQSG (p.u.)	ANN [3]	0.0140	0.0115
	Proposed MPANN	0.0052	0.0056
$\Delta QSVC$ (p.u.)	ANN [3]	0.0204	0.0202
	Proposed MPANN	0.0289	0.0260
ΔQIG (p.u.)	ANN [3]	0.0032	0.0032
	Proposed MPANN	0.003	0.003

Table 2 Comparison of maximum deviations of parameters of AWDHPS Model – III

Parameters of Model – III	Type of Controller	For $\eta q = 3.25$ and ΔQL (p.u.) = 0.034	For $\eta q = 1.25$ and ΔQL (p.u.) = 0.031
ΔV (p.u.)	ANN [3]	-0.002089	-0.001708
	Proposed MPANN	-0.000189	-0.000173
ΔQSG (p.u.)	ANN [3]	0.0148	0.0121
	Proposed MPANN	0.0047	0.0041
$\Delta QSVC$ (p.u.)	ANN [3]	0.0215	0.0210
	Proposed MPANN	0.0308	0.0284
ΔQIG (p.u.)	$\Delta QIG1$ (p.u.)	ANN [3]	0.003
		Proposed MPANN	0.003
	$\Delta QIG2$ (p.u.)	ANN [3]	0.001
		Proposed MPANN	0.001

Table 3 Comparison of Time Domain Specifications of SVC for AWDHPS Model – I

ΔQL in p.u.	0.01		0.05		0.1	
Type of Controller	Proposed MPANN	PI	Proposed MPANN	PI	Proposed MPANN	PI
Overshoot (Mp) %	4.0421	129.7	3.9651	129.6	3.9860	101.1
Settling time (ts) sec.	0.1487	0.216	0.1964	0.217	0.1515	0.210
Rise time (tr) sec.	0.8375	3.9e-4	0.8324	3.4e-4	0.8190	6.1e-5
Peak time, (tp) sec.	0.1767	0.104	0.1694	0.104	0.1491	0.104
Steady state value (YssI)	0.0072	0.010	0.0362	0.049	0.0727	0.099

6.2 Performance of MPANN in AWDHPS Model – II

The two variable parameters such as change in reactive power load (ΔQL) and change in mechanical power input of the induction generator (ΔPIW) are considered as step changes in AWDHPS Model – II. The real time study is carried out in such a way that the reactive power load change is varied from 0.01 to 0.04 p.u. with a span of 1 sec to 1.3 sec and ΔPIW is varied from 0.01 to 0.04 p.u. with a span of 2.2 to 2.65 sec. The performance curves of SVC, SG, IG and voltage are shown in Figure 5 (a to e). The obtained response curves of $\Delta QSVC$ and ΔQSG are similar to AWDHPS Model – I. The variation in wind speed largely influences the response curve of ΔQIG . The obtained response curve of ΔQIG is from 0.0127 to 0.01312 p.u. with a span of 2.604 to 2.605 sec. The performance of voltage variation is high during reactive power load changes and less during change in mechanical power input of the induction generator respectively. Hence the time domain response specifications such as percent over shoot, settling time, rise time, peak time and steady state value of SVC for reactive power load changes from 0.01 to 0.1 p.u. and change in mechanical power input of the induction generator from 0.01 to 0.06 p.u. were observed. The time domain specifications of SVC obtained by the proposed MPANN controller was compared with a PI controller and tabulated in Table 4. It is observed that as the load change occurs from 0.01 to 0.1 p.u. and the reactive power change occurs from 0.01 to 0.06 p.u. settling time is reduced at a faster rate by MPANN controller to damp the oscillations. The percentage peak overshoot is very less. Thus the proposed MPANN controller has shown good performance over the PI controller.

Table 4 Comparison of Time Domain Specifications of SVC for AWDHPS Model – II

ΔQL in p.u.	0.01		0.05		0.1	
ΔPIW in p.u.	0.01		0.03		0.06	
Type of Controller	Proposed MPANN	PI	Proposed MPANN	PI	Proposed MPANN	PI
Overshoot (Mp) %	4.0865	129.9	3.9725	119.7	3.9664	82.60
Settling time (ts) sec.	0.1450	0.217	0.1290	0.215	0.1094	0.203
Rise time (tr) sec.	0.8372	3.5e-4	0.8357	1.4e-15	0.8081	5.1e-4
Peak time, (tp) sec.	0.1763	0.104	0.1742	0.104	0.1323	0.104
Steady state value (YssI)	0.0108	0.014	0.0216	0.074	0.0947	0.129

6.3 Performance of MPANN in AWDHPS Model – III

Three variable parameters are considered in AWDHPS Model – III. The real time study is carried out in such a way that the reactive power load change is varied from 0.01 to 0.04 p.u. with a span of 0.96 sec to 1.4 sec, ΔPIW1 is varied from 0.01 to 0.04 p.u. with a span of 2.2 to 2.5 sec and ΔPIW2 is varied from 0.01 to 0.04 p.u. with a span of 3.4 to 3.6 sec. The performance curves of SVC, SG, IG and voltage are shown in Figure 6 (a to e). The obtained response curves of ΔQSVC and ΔQSG are similar to AWDHPS Model – I and II. The entire study is carried out in the time span 0.85 sec. to 3.6 sec. The reactive power ratings of two induction generators are 0.13 and 0.04 p.u. respectively. Based on the rating of the induction generators, it is better to consider the variation of ΔPIW1 as higher value than ΔPIW2 . Hence, in the study, ΔPIW1 is varied from 0.01 to 0.06 p.u. and ΔPIW2 is varied from 0.03 to 0.08 p.u. Moreover the reactive power load changes from 0.01 to 0.1 p.u. are considered. The time domain response specifications such as rise time, settling time, percent over shoot, peak time and steady state value of SVC for above variations were observed. The time domain specifications of SVC obtained by the proposed MPANN controller was compared with a PI controller and tabulated in Table 5. The performance of proposed MPANN controller is found to be better than PI controller. From the time domain response specifications of SVC of the three models given in Tables 3, 4 and 5 it is observed that peak time (t_p) are nearly same. The percentage of peak overshoot is reduced when ΔQL is varied from 0.01 to 1 p.u. because the maximum reactive power

Table 5 Comparison of Time Domain Specifications of SVC for AWDHPS Model – III

ΔQL in p.u.	0.01		0.05		0.1	
ΔPIW1 in p.u.	0.01		0.03		0.06	
ΔPIW2 in p.u.	0.03		0.05		0.08	
Type of Controller	Proposed MPANN	PI	Proposed MPANN	PI	Proposed MPANN	PI
Overshoot (Mp) %	4.0865	129.9	3.9725	119.7	3.9664	82.60
Settling time (ts) sec.	0.1450	0.217	0.1290	0.215	0.1094	0.203
Rise time (tr) sec.	0.8372	3.5e-4	0.8357	1.4e-15	0.8081	5.1e-4
Peak time, (tp) sec.	0.1763	0.104	0.1742	0.104	0.1323	0.104
Steady state value (YssI)	0.0108	0.014	0.0216	0.074	0.0947	0.129

supported by SVC is assumed to be 0.85 p.u. Generally the rise time (t_r) increases as ΔQL is varied from 0.01 to 1 p.u. in all the three models. In the case of increase in ΔQL and ΔPIW the settling time (t_s) decreases. The steady state value (Y_{ss}) of SVC in AWDHPS Model – III is high because of the cumulative effect of three variable parameters of the model. Hence it is represented in a simple way by the expression, $Y_{ssI} < Y_{ssII} < Y_{ssIII}$. Thus the AWDHPS Models are simulated in dSPACE environment and in this study the Knob is varied to increase or decrease the reactive power load and mechanical power of induction generators in real time environment for a desired time specification. The performance curves are visualized for the various components present in the models.

7 Conclusion

This paper presented the automatic reactive power control of AWDHPS by tuning SVC using the proposed MPANN. The MATLAB/simulink models of three different AWDHPS were built by integrating the proposed MPANN as the controller for tuning the SVC. The potential of proposed MPANN controller was demonstrated by varying the disturbance parameters such as change in reactive power of the load (ΔQL), the change in mechanical power input of single induction generator (ΔPIW) and the change in mechanical power input of two induction generators ($\Delta PIW1$, $\Delta PIW2$) in three different AWDHPS models. Then the above MATLAB/simulink models of AWDHPS were built in dSPACE real time environment. The real time assessment of the models was carried out by dynamically varying the parameters in control desk of dSPACE Software with DS1104 R & D controller board mounted in personal computer. The proposed MPANN controller in dSPACE environment has performed well compared to the ANN controller in MATLAB/simulink present in recent literature. Specifically the change in system voltage (ΔV) was significantly reduced by the MPANN controller. The time domain specifications of SVC obtained by the MPANN controller and a PI controller were compared. The proposed MPANN controller has shown good performance over the PI controller. The static and dynamic response curves were depicted. The reactive power deviations and time domain specifications were tabulated.

Appendix A: AWDHPS Data

AWDHPS Parameters	AWDHPS data – I	AWDHPS data – II	
		IG1	IG2
Wind Capacity (kW)	150	150	50
Diesel Capacity (kW)	150	150	–
Load Capacity (kW)	250		300
Base Power (kVA)	250		300
<u>SG:</u>			
PSG (pu kW)	0.4		0.333
QSG (pu kVAR)	0.2		0.162
Eq' (pu)	1.1136		0.9804
δ_o	21.05		17.2483
Eq (pu)	0.9603		1.1242
V (pu)	1.0		1.0
x _d (pu)	1.0		1.0
x' _d (pu)	0.15		0.15
T' _{do} (pu)	5.0		5.0
<u>IG:</u>			
PIG (pu kW)	0.6	0.5	0.1667
QIG (pu kVAR)	0.189	0.1343	0.0426
PIW (pu kW)	0.75	0.63	0.21
η_{IG} (%)	80	80	80
r ₁ = r ₂ ' (pu)	0.19	0.19	0.55
x ₁ = x ₂ ' (pu)	0.56	0.56	1.6
s (%)	–4.1	–3.49	–3.37
<u>Load:</u>			
PL (pu kW)	1.0		1.0
QL (pu kVAR)	0.75		0.75
Pf (lag)	0.8		0.8
<u>SVC:</u>			
QSVC (pu kVAR)	0.739		0.7649
QC (pu kVAR)	0.85		0.87961
α (radians)	2.443985		2.4452
T α (s)	0.005		0.005
T _d (s)	0.001667		0.00167
<u>IEEE Type-I Excitation System:</u>			
KA	40		40
TA (s)	0.05		0.05
KF	0.5		0.5
TF (s)	0.715		0.715
KE	1.0		1.0
SF (s)	0.0		0.0
TE (s)	0.55		0.55

Appendix B: Constant Values of AWDHPS

AWDHPS Model – I:

$K_1 = 0.15$; $K_2 = 0.793232$; $K_3 = 6.22143$; $K_4 = -7.358895$; $K_5 = 0.126043$;
 $K_8 = 1.478$; $K_9 = 1.0$; $K_V = 0.6667$; $K_\alpha = 0.446423$ and
 $TV = 0.000106$ seconds.

AWDHPS Model – II:

$K_1 = 0.15$; $K_2 = 0.793232$; $K_3 = 6.22143$; $K_4 = -7.35889$, $K_6 = 0.4961$;
 $K_7 = -0.122068$; $K_8 = 1.478$; $K_9 = 1.0$, $K_V = 0.6667$; $K_\alpha = 0.446423$
and $TV = 0.000106$ seconds.

AWDHPS Model – III:

$K_1 = 0.15$; $K_2 = 0.811744$; $K_3 = 6.36662$; $K_4 = -7.0915$, $K_{61} = 0.4961$;
 $K_{62} = 0.39575$; $K_{71} = -0.122068$; $K_{72} = -0.026977$; $K_8 = 1.52976$;
 $K_9 = 1.0$; $K_V = 0.66667$, and $TV = 0.0001061$ seconds.

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Biography

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