

Analysis of Standalone Hybrid Power Systems with reference to the Reactive Power Management

V. Vaishnavi* and P. Linga Reddy

Electrical and Electronics Engineering, K L University, Vaddeswaram, Guntur District - 520002, Andhra Pradesh, India; vaishnavishesu@gmail.com, lingareddypotlaeee@kluniversity.in

Abstract

Standalone hybrid systems are need of the hour in electrical power sector. The reactive power support is most vital issue in the voltage point of view. Wind energy has received the special attention of researchers in recent times. Attempts to generate electricity from wind energy have been made since the end of nineteenth century. A single renewable energy source may not be able to meet the load demands apart from the fact that continuous supply of energy may not be ensured. Here comes the importance of Hybrid energy systems such as Wind-diesel, Wind-PV. Advanced FACTS technologies have utilized for reactive power support to the system. The fuzzy logic has implemented in the control circuit of STATCOM which is relatively advantageous compared to conventional PI controller. The control strategy is verified through model simulation study whose results conform the significance of the control methodology incorporated in the paper.

Keywords: Permanent Magnet Induction Generator (PMIG), Static Synchronous Compensator (STATCOM), Synchronous Generator (SG), Wind-diesel Hybrid System

1. Introduction

Ever growing electric power demand by infinite consumers all around the world pushes for reforms in power sector. One of the most lucrative ways to meet this surplus demand is by encouraging of non-conventional energy sources and development of hybrid power systems to cater the needs of a bunch of consumers. If the renewable energy sources are sole power sources and not connected to the grid, they can be termed as standalone or isolated hybrid systems. If the renewable energy systems are connected to the grid directly, then they are called grid connected systems. This type of generation is called distributed generation or embedded generation. Ideally, diesel generator coupled with solar or wind¹ form a hybrid energy system. Sometimes, the diesel systems are coupled with synchronous generators which are used to meet the needs of remote areas which are not accessible to power. Induction generators are also an alternate option which can link up with the diesel system to produce power in an isolated mode of operation of the power system. But the problem with induction generators

is that regulation of voltage is not very satisfactory and also it requires exciting current which significantly affects the output power and PF¹.

An alternative solution to this problem is PMIG. The rotor of the induction machine is embodied with permanent magnets, hence the name permanent magnet induction machine. Numerous models have been prescribed in literature regarding the modeling of PMIG such as d-q axis model, per unit model; etc. The main objective is that there should not be any power imbalance between the source and the load which would otherwise cause severe disturbances in the power system. This calls for dynamic reactive power compensation according the changing system conditions. Advanced FACTS technology based devices are readily available which makes the job of reactive power supplement very easy. Voltage Source Converter (VSC) is the type of power supplement which is capable of KW as well as KVAR supply. STATCOM² is chosen for the reactive power requirement.

Small signal model of the isolated hybrid system along with FACTS device such as STATCOM is simulated with

*Author for correspondence

induction generator as well as permanent magnet induction generator type and also with various ratings of the machines. The Square of the Integral² Error (ISE) is the evaluation criteria of determining the STATCOM control parameters. The dynamic response of the system with changes in load (Q) and also change in the input power of the wind generator is has been studied for the two types of systems.

2. Mathematical Modeling

The mathematical model of standalone hybrid energy system with STATCOM as depicted in Figure 1. The P and Q of the Wind-Diesel system under steady-state conditions are as shown³

$$P_{PMIG} + P_{SG} = P_L \quad (1)$$

$$Q_{SG} + Q_{com} + Q_{PMIG/IG} = Q_L \quad (2)$$

The change in the reactive power should result in difference in the bus voltage which is given as

$$\Delta V(s) = \frac{K_V}{1+sT_V} [\Delta Q_{SG}(s) + \Delta Q_{com}(s) + \Delta Q_{PMIG/IG}(s) - \Delta Q_L(s)] \quad (3)$$

where, the symbols have their usual meanings

T_V represents the time constant and K_V represents the gain

Simultaneously, loads associated with the system will be subjected to fluctuations due to this change because of the system voltage-load characteristics as given below

$$D_V = \frac{\partial Q_L}{\partial V} \quad (4)$$

The total loads in exponential representation is given by

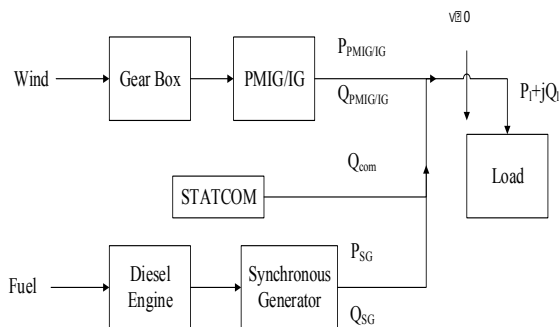


Figure 1. Standalone hybrid system considered in this paper.

$$Q_L = c_1 V^q \quad (5)$$

$$D_V = \frac{\Delta Q_L}{\Delta V} = q \cdot \frac{Q_L}{V^q} \quad (6)$$

A standard IEEE type-1 excitation system is chosen to model the SG while neglecting the effect of saturation effect (S_F) which is represented in Figure 2. The equations related to the excitation system are given as³

$$\Delta E_{fd}(s) = \frac{1}{K_E + sT_E} \Delta V_a(s) \quad (7)$$

$$\Delta V_a(s) = \frac{K_A}{1+sT_A} (\Delta V(s) - \frac{K_F}{T_F} \Delta E_{fd}(s) + \Delta V_f(s)) \quad (8)$$

$$\Delta V_f(s) = \frac{K_F}{T_F} \cdot \frac{1}{1+sT_F} \Delta E_{fd}(s) \quad (9)$$

$$\Delta E'_q(s) = \frac{1}{(1+sT_G)} [K_1 \Delta E_{fd}(s) + K_2 \Delta V(s)] \quad (10)$$

And K_1 is given by;

$$K_1 = \frac{X'_d}{X_d}; K_2 = [(X_d - X'_d) \cos \delta] / X_d$$

And $T_G = T_{d0}' X'_d / X_d$

Changes in the reactive power of synchronous generator is reflected by

$$\Delta Q_{SG}(s) = K_3 \Delta E'_q(s) + K_4 \Delta V(s) \quad (11)$$

K_3 and K_4 are given as;

$$K_3 = V \cos \delta / X'_d; K_4 = [E' \cos \delta - 2V] / X'_d$$

Similarly, the reactive power changes of PMIG is given by

$$\Delta Q_{PMIG}(s) = K_5 \Delta V(s) \quad (12)$$

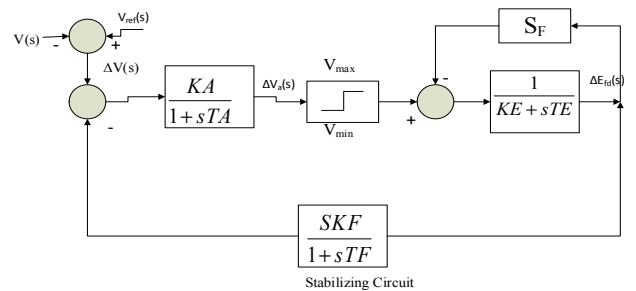


Figure 2. IEEE type-I excitation system.

$$K_5 = \frac{-2X_{eq}V}{R_Y^2 + X_{eq}^2} + \frac{V^2}{X_C} \left\{ \frac{(3aV^2 + 2bV + c)}{(3X_C^3)} - \frac{2}{V} \right\} \quad (13)$$

$$R_Y = R_P + R_{eq} \quad (14)$$

$$R_P = \frac{r_2}{s} (1 - s) \quad (15)$$

$$X_C = (aV^3 + bV^2 + cV + d)^{1/3} \quad (16)$$

In other words, the equations can be represented as

$$\Delta Q_{PMIG}(s) = K_6 \Delta P_{TW}(s) + K_7 \Delta V(s) \quad (17)$$

where,

$$K_6 = \frac{-2X_{eq}R_YV^2}{(R_Y^2 + X_{eq}^2)(2R_Y(P_{TW} - P_{coreloss}) + V^2)} \quad (18)$$

$$K_7 = \left[K_{c1} + \frac{V^2}{X_C} \left\{ \frac{(3aV^2 + 2bV + c)}{(3X_C^3)} - \frac{2}{V} \right\} \right] \quad (19)$$

where,

$$K_{c1} = \frac{-2X_{eq}V}{R_Y^2 + X_{eq}^2} * \left[1 + \frac{2R_YR_PV^2}{(R_Y^2 + X_{eq}^2)(2R_Y(P_{TW} - P_{coreloss}) + V^2)} \right] \quad (20)$$

If the capacitance is not considered PMIG is electrically equivalent to IG.

The STATCOM is electrically equivalent to voltage source in synchronous mode which produces voltages without any unbalancing and equipped with fast control strategies STATCOM typically which includes dc capacitor and coupling transformer and reactive power control accomplished by STATCOM⁴ is given in Figure 3. The real power injection is given by

$$Q_{com} = kV_{dc}^2B - kV_{dc}VB \cos(\alpha - \delta) + kV_{dc}VG \sin(\alpha - \delta) \quad (21)$$

The kV_{dc} term in the equation is constant/steady state component including voltage across the capacitor.

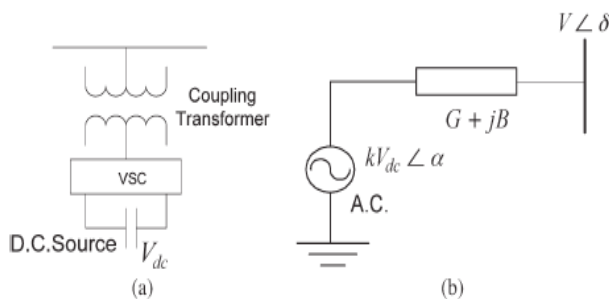


Figure 3. (a) STATCOM (b) STATCOM model.

Further,

$$Q_{com} = kV_{dc}^2B - kV_{dc}VB \cos \alpha \quad (22)$$

The STATCOM equation in linearised form is given by⁴

$$\Delta Q_{com}(s) = K_8 \Delta \alpha(s) + K_9 \Delta V(s) \quad (23)$$

where,

$$K_8 = kV_{dc}VB \sin \alpha \quad (24)$$

$$K_9 = -kV_{dc}B \cos \alpha \quad (25)$$

3. Proposed System Transient Performance

The simulation results of hybrid system configurations are given in Table 1⁵. The ideal gain numerical of the STATCOM using the standard criterion is given in Table 1. It is found that the gain constant would be larger if the STATCOM rating is less or the deviation between the output and demand is more. Table 2⁵ gives the values of constants of W-D1, W-D2 and W-D3. Also values of constants/parameters of W-D1, W-D2, and W-D3 are given in Table 3⁵.

Figure 4 depicts the case for step increase of 1% in the load and with no alteration of input power of wind system. The wind turbine size increases with IG increases with the increment of the voltage deviation at peak value. The increment in the load is supplemented by the compensator installed in the system. In case of PMIG, with

Table 1. Gain values of STATCOM for three hybrid systems using IG and PMIG

Wind-diesel System or W-D System Data		Constant slip		Variable slip	
		K_p	K_i	K_p	K_i
W-D1	IG	39	5090	31	5000
W-D2	IG	53	6727	43	6636
W-D3	IG	70	10899	68	10700
W-D1	PMIG	37	6181	36	6000
W-D2	PMIG	52	8363	51	8181
W-D3	PMIG	68	14434	66	14242

Table 2. Values of constants of three systems of Wind-Diesel

W-D1			W-D2		W-D3	
Constants	IG	PMIG	IG	PMIG	IG	PMIG
K_1	0.15	0.15	0.15	0.15	0.15	0.15
K_2	0.79327	0.7932	0.7590	0.7590	0.6737	0.67374
K_3	6.22178	6.221	5.9531	5.95319	5.2842	5.2842
K_4	-7.8249	-7.824	-9.6627	-9.6627	-8.082	-8.082
K_5	0.1016	-0.666	0.0861	-0.6815	0.056	-0.7116
K_6	0.444	0.444	0.4535	0.4535	0.3034	0.3034
K_7	-0.0974	-0.865	-0.0828	-0.8505	-0.0427	-0.8103
K_8	5.15286	3.36	4.59882	3.10	3.56058	2.5727
K_9	-3.8347	-2.5	-3.4260	2.3099	-2.6522	-1.9114
K_v	0.6667	0.667	0.6667	0.667	0.6667	0.667
T_v	5.43E-04	5.43E-04	5.43E-04	5.43E-04	5.43E-04	5.43E-04

increase in the offset of the voltage deviation, the wind turbine size with PMIG decreases.

In transient condition, the reactive power is supported by STATCOM and SG while in case of steady state it is supplemented by STATCOM. Absence of a compensator results in deviations of greater magnitude which cannot be articulated by AVR (Automatic Voltage Regulator) along with SG. STATCOM acts as a compensator to balance the reactive power and supplement the reactive power in case necessary with rapid and quick action no matter the type of disturbance encountered by the system.

4. Including of Saturation Function

In the base paper the Saturation Function (SF) in the IEEE type 1 Excitation system is neglected⁵ i.e. SF = 0. So

Table 3. Values of constants of three systems of Wind-Diesel.

System Parameter	W-D1	W-D2	W-D3
Wind Capacity(KW)	1500	1000	500
Diesel Capacity(KW)	1500*	1500*	1500*
Load Capacity(KW)	2500	2000	1500
Base Power(KVA)	2500	2000	1500
SG			
$P_{SG}(p.u)$			
$Q_{SG}(p.u)$	0.4	0.5	0.6667
$E_g(p.u)$	0.2	0.242	0.3333
$E'_g(p.u)$	1.1136	1.1108	1.094
$\delta(degree)$	0.9603	0.92564	0.838
$X_d(p.u)$	21.05	26.75	37.567
X'_d	0.15	0.15	0.15
$T'_{do}(p.u)$	1.0	1.0	1.0
	5.0	5.0	5.0
IG			
$P_{IG}(p.u)$	0.6	0.5	0.333
$Q_{IG}(p.u)$	0.2906	0.242161	0.161
$\eta(\%)$	90	90	90
$r_1=r'_2(p.u)$	0.19	0.228	0.25
$x_1=x_2(p.u)$	0.56	0.685	0.74
$S(\%)$	-4	-4	-3
PMIG			
P_{PMIG}	0.6	0.5	0.333
Q_{PMIG}	0	0	0
$\eta(\%)$	90	90	90

(Continued)

r ₁ =r' ₂ (p.u) x ₁ =x' ₂ (p.u) S(%)	0.19 0.56 -4		0.228 0.685 -4		0.25 0.74 -3	
LOAD P _L (p.u) Q _L (p.u) Power Factor	1.0 0.75 0.8		1.0 0.75 0.8		1.0 0.75 0.8	
IEEE Type-1 Excitation System						
K _A	40		40		40	
K _E	1.0		1.0		1.0	
K _F	0.5		0.5		0.5	
T _A (seconds)	0.05		0.05		0.05	
S _p T _E (seconds)	0,0.55		0,0.55		0,0.55	
STATCOM						
T _i (ms)	10-50		10-50		10-50	
T _α (ms)	0.2-0.3		0.2-0.3		0.2-0.3	
T _d (ms)	1.67		1.67		1.67	
Reactive Power Data	IG	PMIG	IG	PMIG	IG	PMIG
	0.84 53.3	0.55 53.39	0.61 53.3	0.508 53.39	0.581 53.3	0.42 53.3
Q _{com} (p.u) α(degree)						

Herein my paper I am including the saturation function. Saturation function is represented by its Describing function. The representation of Describing Function is as shown,

$$\frac{K_N(X)}{K} = 1 \quad ; X < S$$

$$= \frac{2}{\pi} \left\{ \sin^{-1}(S/X) + (S/X) \sqrt{1 - (S/X)^2} \right\} ; X > S$$

The terms are defined as;

X = Amplitude of Input Sinusoid

$K_N(X)$ = Describing Function

K = Slope

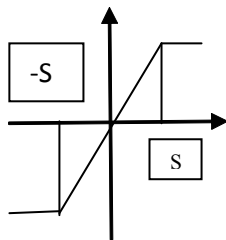


Figure 5 shows the transient response of Wind and Diesel system using IG for increase in load by 1% and with

time in seconds on X-axis and change in voltage in per unit on Y-axis. From the graph it is observed that by including the saturation function the settling time decreases from 0.007sec to 0.005sec, also the peak over shoot decreases from 4×10^{-4} to 3.5×10^{-4} . It is also observed that the peak time remains same.

When we use Wind-Diesel system with PI controller we get more deviations and also the settling time increases. So to avoid these drawbacks we are going to use the following system.

5. Wind-PV System

The system is modified by placing PV in place of diesel based energy source. Also the PI control employed in the control circuit of STATCOM is replaced with Fuzzy logic controller. The PV⁶ system is appropriately modeled and suitably incorporated in the small signal analysis. The figures depict the performance of the system with the modified model.

The controller using Fuzzy logic resembles⁷ the logic belonging to mankind. Fuzzy Logic control is more advantageous than PI and PID controllers because this

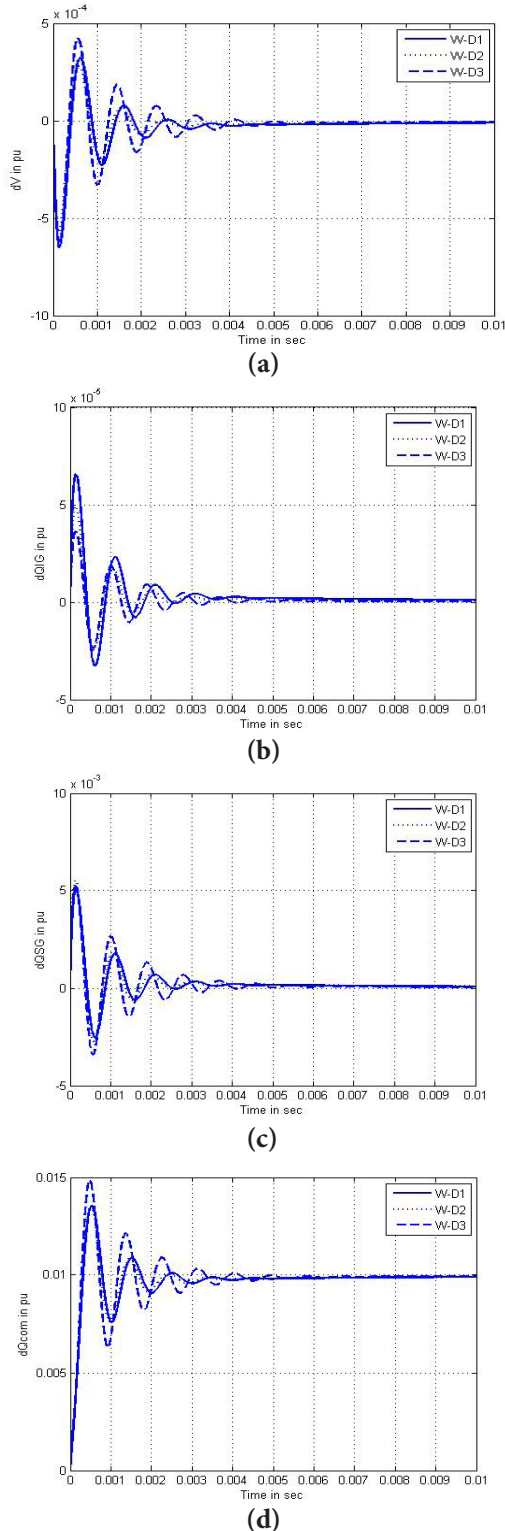


Figure 4. Dynamic response of the proposed system configurations with IG under transient conditions with 1% increase in load. (a) Voltage change vs. time (b) Reactive power change of IG vs. time (c) SG Reactive power change vs. time (d) STATCOM reactive power change vs. time.

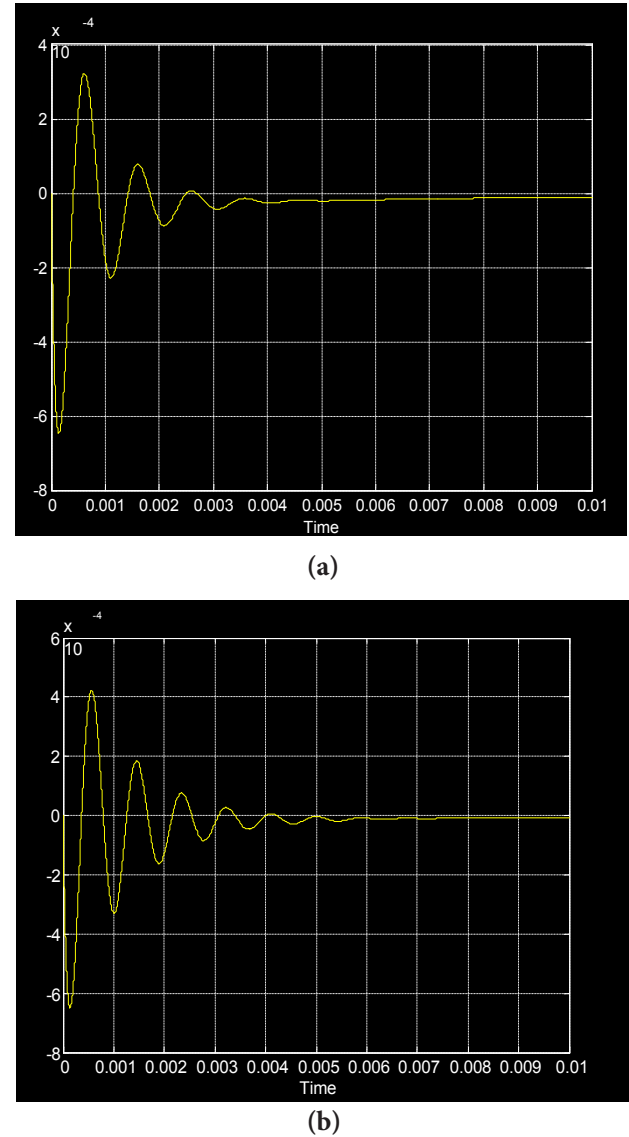


Figure 5. Waveforms with and without saturation function. (a) With saturation function (b) Without saturation function.

controller is more Flexible when compared with other types of controllers. Unlike PI controllers these controller has multiple inputs and multiple outputs. The process involves creating of membership values after choosing proper membership function. As shown⁸ in Figure 6 there are three steps in this controller.

6. Modeling Equations

Solar equivalent circuit⁹

$$I = V_o/s/R1$$

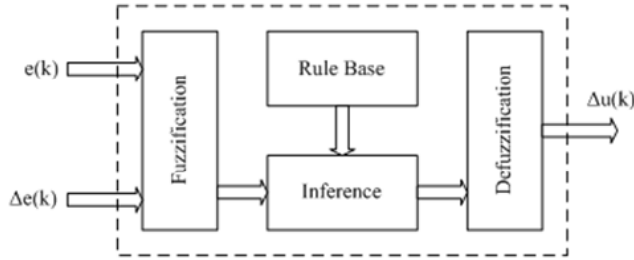


Figure 6. Fuzzy logic controller.

$$I = V_o / sR_1$$

$$\frac{V_o}{I} = sR_1(a)$$

Boost converter equations¹⁰

$$V_o(s) = L \frac{di}{dt} + iR$$

$$\frac{V_o}{s} = LSI + IR$$

$$\frac{V_o}{s} = I(LS + R)$$

$$\frac{V_o}{I} = S(LS + R)$$

$$V_{o1} = IR_1$$

$$I = \frac{V_{o1}}{R}$$

$$\frac{V_o}{V_{o1}/R} = S(LS + R)$$

$$\frac{R \cdot V_o}{V_{o1}} = \frac{R}{S(LS + R)}$$

$$\frac{V_{o1}}{V_o} = \frac{R}{S(LS + R)}$$

$$\frac{V_o'}{V_o} = \frac{1}{s(L/RS+1)} \frac{V_o'}{V_o} = \frac{1}{s(L/RS+1)}(b)$$

From (a) $V_o = SIR_1 V_o = SIR_1$

From (b) $\frac{V_o'}{V_o} = \frac{1}{s(L/RS+1)}$

$$V_o' = \frac{V_o}{s(L/RS+1)}$$

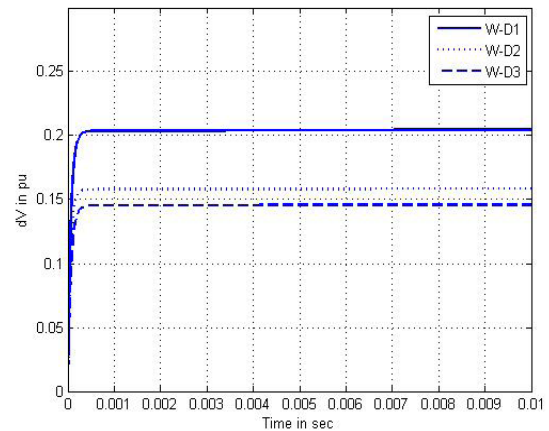
$$V_{o1} = \frac{SIR_1}{s(L/RS+1)}$$

$$V_{o1} = \frac{IR_1}{(L/RS+1)}$$

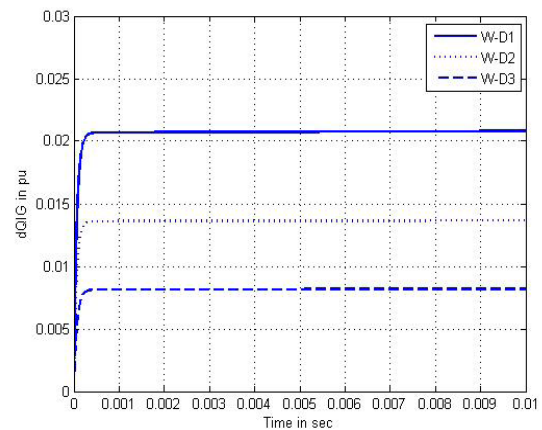
$$\frac{V_{o1}}{I} = \frac{R_1}{(L/RS+1)} = \frac{R_1}{(\tau S+1)}$$

($\tau = 1/R$)

Figure 7 shows the responses of Wind-PV system for an increase of 1% in load. When comparing with Wind-Diesel system with IG the settling time decreases from 0.007sec to 0.001sec, Also the deviations are reduced when compared with the Wind-Diesel System.



(a)



(b)

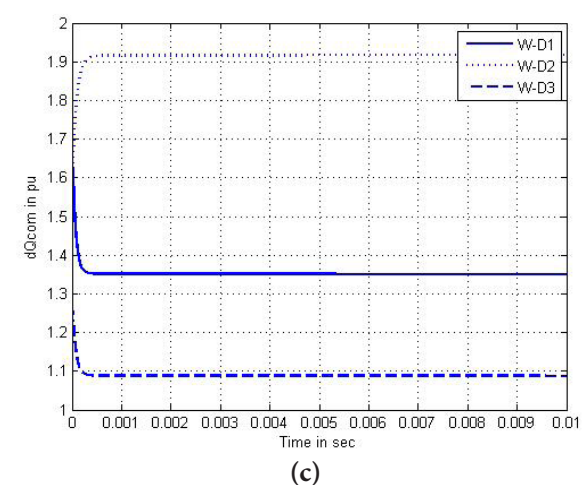
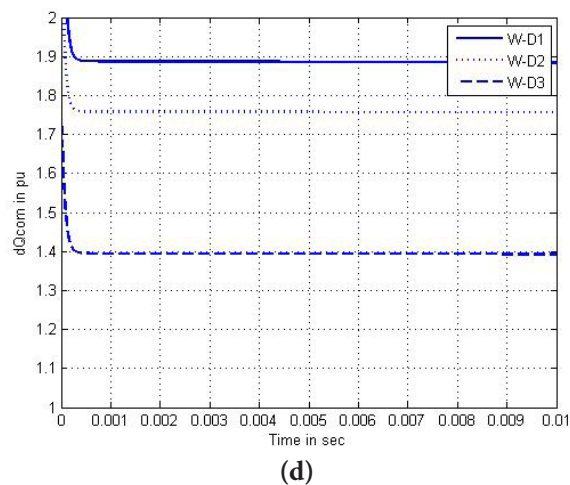
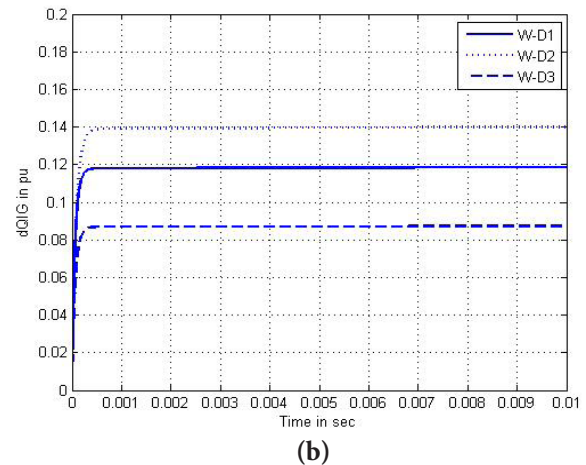
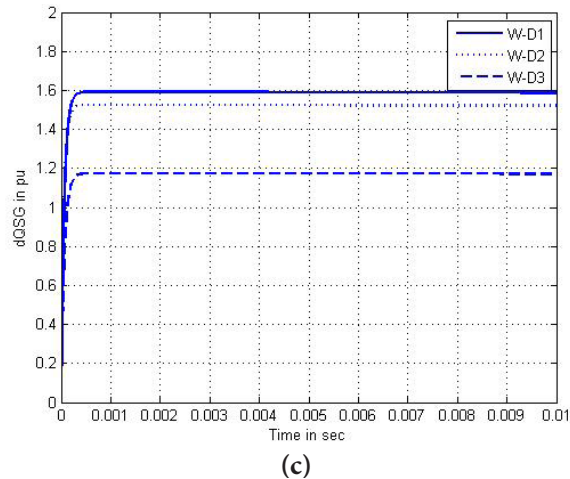


Figure 7. Transient responses of the system with 1% load increment. (a) Change in voltage vs. time (b) Change in reactive power of IG vs. time (c) Change in reactive power of SG vs. time (d) Change in reactive power of STATCOM vs. time.

Figure 8. Transient response of the system with PMIG for each 1% increase in Load and input wind. (a) Change in voltage vs. time (b) SGs change in reactive power vs. time (c) Change in reactive power of STATCOM vs. time.

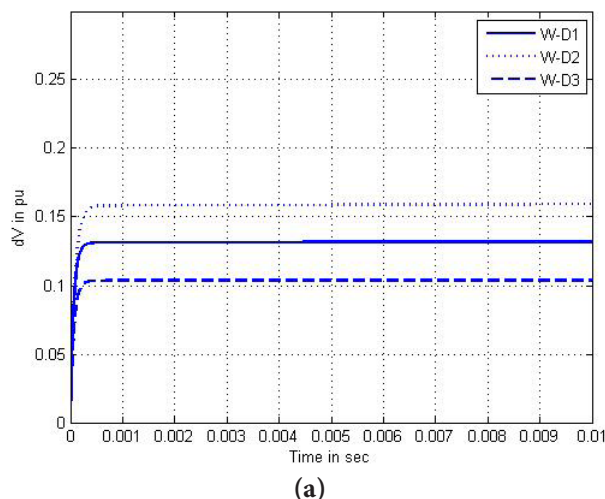


Figure 8 shows the response of the Wind and Photovoltaic system using PMIG for 1% load increment and 1% step increase in input power of wind system. When comparing with Wind-Diesel system with PMIG the settling time decreases from 0.006sec to 0.001sec, also the deviations are reduced when compared with the Wind-Diesel System.

7. Conclusion

The reactive power control strategies for various system configurations with PMIG and IG are evaluated in the simulation study. It is observed that interconnected hybrid systems are effective solution to meet the remote and inaccessible load demand. The compensator used for reactive

power support is STATCOM. The configuration of the hybrid system is changed from wind-diesel to wind-PV and performance evaluation is carried in small signal analysis mode. The controller employed in control circuit of the STATCOM is changed from Proportional Integral (PI) based control to Fuzzy logic based control. It is found out that by using fuzzy controller the settling time decreases and also the peak over shoot decreases which is advantageous than PI control. Also by including the saturation function the settling time and also the peak over shoot decreases when compared with saturation function neglected.

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