Intelligent Technique Based Reactive Power Compensation of Isolated Hybrid Power System

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Abstract-This paper presents the effective utilization analysis of STATCOM for the reactive power compensation during any sudden load disturbances in an Isolated Hybrid Power System (IHPS) integrating Induction Generator (IG) coupled Dish Stirling Solar Thermal System (DSTS) -micro hydro power system and a synchronous generator coupled diesel generation system. Considering the volatile nature of the solar radiation and the random variation in reactive power absorbance by IG and reactive load, STATCOM is employed with Proportional Integral (PI) controller to maintain the system voltage regulation. Gains of PI controller are optimized with the help of modern meta-heuristic Flower Pollination Algorithm (FPA) and its performance is compared with the Genetic Algorithm (GA) and Particle Swarm Optimization algorithm(PSO). Implication of the simulation results discloses that the FPA based PI tuned controller helps in improving the voltage stability of the IHES under uncertain load disturbances.

Keywords: DSTS, Micro Hydro, Diesel, STATCOM, Optimization and Transient Stability

1. Introduction

Diesel generators are main source of power to remotely located areas. Installation and operating cost of diesel generators are too high and to overcome this renewable energy resources are integrated with diesel power plants [4, 23]. For power generation by diesel and wind, synchronous and induction generators are used. Low investment and maintenance cost,reduced amount of frequency control problems are noteworthy advantages of induction generator. Due to its requirement of magnetizing current as a source of excitation, performance of induction generator is poor in terms of voltage regulation. Because of this and reactive power demand by load there is mismatch between generated and consumed reactive power. As an outcome, there occurs voltage fluctuation at generator terminal reducing quality of power supply and it requires some compensation [5, 6]. Reactive power requirement by induction generator is supplied by capacitor bank in case of grid connected system where excess reactive power by the capacitor is absorbed by the grid. In IHPS the reactive power requirement by induction generator and load varies and if capacitor banks are used for reactive power compensation, transient in voltage may occur due to mismatch in reactive power generation and demand. Switched capacitor is used only if the system is grid connected or reactive power requirement of the system remains constant [23].

To overcome this, reactive power compensating devices like SVC and STATCOM are required [22,9].Capacitive and inductive reactive power in STATCOM is generated by voltage source inverter whereas SVC requires external capacitor and inductor. In addition, response time of STATCOM is high compared to SVC.STATCOM has many advantages over SVC and this paper investigates the performance ofSTATCOM controller in an isolated DSTS-micro hydro-diesel hybrid power system.

In literature, to compensate reactive power for wind-diesel hybrid power system, SVC and it's types with controller gains tuned by conventional methods have been reported [4-6]. Performances of STATCOM and SVC in isolated wind diesel system are compared and it is concluded that STATCOM provides better stability than SVC[21].Based on power flow modelling, small signal model of STATCOM used for reactive power compensation containing three blocks was obtained. Depending on requirement, arrangement of regulator may vary like an amplifier with a gain and time constant, proportional integral type or lead lag type [13]. Performance of STATCOM for reactive power compensation of IHPS incorporating induction generator and permanent generator has been analysed [23].Recently, automatic tuning of controller parameters using meta-heuristics algorithms has gained much interest [16]. Gain of PI controller in STATCOM incorporated in wind-diesel hybrid system was optimised keeping the parameters of controller in automatic voltage regulator (AVR) constant[1-2]. The controller parameters of the SVC and AVR were optimised simultaneously by GA under random load change with fixed reactive power consumption by the IG, which is not realistic [27]. In addition to optimizing the controller parameters of STATCOM, the system reactive power demand and voltage variation will be reduced if the load interaction with the system is considered [18]. It is found that the system reactive power demand by compensating devices and voltage variation will be reduced if optimized controllers were used [19]. The major contributions of the present work are summarised as follows

(i) Reactive power compensation of DSTS-micro hydro-diesel system under 1 % load disturbance with constant power input to DSTS and micro hydro.

(ii) Reactive power compensation of DSTS-micro hydro-diesel system under 1 % load disturbance and 1 % input power disturbance to DSTS and micro hydro.

(iii) Tunable parameters of STATCOM in isolated hybrid power system are optimized with the help of GA, PSO and FPA algorithms.

(iv) Compared the performance of FPA optimised PI controllers with their PSO and GA optimised counterparts in terms of terminal voltage response.

2. Mathematical modelling of the system

The reactive power demand equations for the studied power system model is as follows,

$$\Delta Q_{SG}(s) + \Delta Q_{Statcom}(s) - \Delta Q_{Load}(s) - \Delta Q_{IG1}(s) - \Delta Q_{IG2}(s) = 0 \quad (1)$$

and the transfer function for incremental change in load can be written as,

$$\Delta V(s) = \left(\frac{K_v}{1+sT_v}\right)[\Delta Q_{SG}(s) + \Delta Q_{Statcom}(s) - \Delta Q_{Load}(s) - \Delta Q_{IG1}(s) - \Delta Q_{IG2}(s)] \quad (2)$$

The disturbance in the reactive power demand of the load (ΔQ_{Load}) will lead to the change in system voltage which results in incremental change in reactive power demand of the other components. The left hand side of (1) represents the net incremental reactive power and this change in reactive power demand will have effect on the change in system voltage (2). But as per the recommendation of the grid, the voltage change should be within its permissible limit and hence terminal voltage profile should be maintained properly [1]. Block diagram representation of the IHPS is shown below in Figure.1

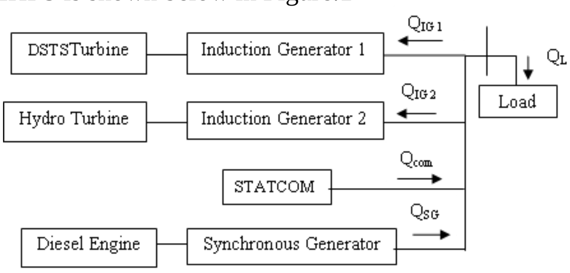


Figure 1. Block Diagram of Isolated Hybrid Power System

2.1. Modelling of SG Block

The incremental change in reactive power of SG is given by [4]

$$\Delta Q_{SG}(s) = K_1 \Delta E_q'(s) + K_2 \Delta V(s) \quad (3)$$

Where

$$K_1 = \frac{V\cos\delta}{X_d'} \quad (4)$$

$$K_2 = \frac{E_q'\cos\delta - 2V}{X_d'} \quad (5)$$

The transfer function equation for state variable $\Delta E_q'(s)$ is obtained from the flux linkage equation of the SG along with the excitation system (IEEE type I), as given in [4, 21]

$$\Delta E_q'(s) = \left(\frac{1}{1+sT_g}\right)[K_3 \Delta E_{fd}(s) + K_4 \Delta V(s)] \quad (6)$$

$$K_3 = \frac{X_d'}{X_d} \quad (7)$$

$$K_4 = \frac{[(X_d - X_d')\cos\delta]}{X_d'} \quad (8)$$

$$T_g = T_{d0}' \frac{X_d'}{X_d} \quad (9)$$

2.2. Modelling of IG Block (DSTS and micro hydro)

The Dish-Stirling Solar Thermal System comprises parabolic dish, receiver and the tracking device [24].DSTS systems track the sun and concentrates solar energy into a cavity receiver [28]. Parabolic dish has concentration ratio as high as 3000. The absorbed solar energy is transferred to the working fluid (water, hydrogen or helium gas) in Stirling engine by the receiver. The engine then converts the absorbed thermal energy to a mechanical power by compressing the working fluid when it is cool and expanding it when it is hot [17,26]. Stirling engine is coupled to induction generator (IG) to generate electricity [3, 11].

DSTS systems have demonstrated the highest efficiency than any other solar power technology[25-26]. The output power of DSTS [27] is given by

$$P_{DSTS} = 0.015 P_m V_p f \quad (10)$$

where P_{DSTS}, P_m, V_p and f are thermal power output, mean cycle pressure, displacement of power piston and frequency respectively.P_{DSTS} serves as input to IG and hence P_{DSTS}equal to P_{IG}. A constant slip model IG is considered when Power input to DSTS is assumed constant. For small perturbation, reactive power absorbed by the variable slip IG is [6, 12]

$$\Delta Q_{IG1}(s) = K_6 \Delta P_m(s) + K_7 \Delta V(s) \quad (11)$$

Where

$$K_6 = \frac{X_{eq}}{R_p - (R_y^2 + X_{eq}^2)/2R_y} \quad (12)$$

BUPT

$$K_7 = \frac{2V}{R_y^2 + X_{eq}^2}\left[X_{eq} - \frac{R_p X_{eq}}{\left(R_p - (R_y^2 + X_{eq}^2)\right)/2R_y}\right] \quad (13)$$

The output of micro-hydro turbine can be coupled to IG and reactive power absorbed by IG coupled to micro-hydro turbine is given by (11)

2.3. Modelling of STATCOM

STATCOM are of different configuration like an amplifier with a gain and time constant, a twin lead lag type and PI type [10]. A PI controller based STATCOM is considered and reactive power supplied by STATCOM can be written as [3, 7]

$$\Delta Q_{STATCOM}(s) = K_9 \Delta V(s) + K_8 \Delta\propto(s) \quad (14)$$

where

$$K_8 = kV_{dc}VB_{ST}\sin\propto \quad (15)$$

$$K_9 = -kV_{dc}B_{ST}\cos\propto \quad (16)$$

From the above equation it is clear that reactive power supplied can be controlled by varying voltage and firing angle.

3. Problem Formulation

The control parameters of PI controller in STATCOM are optimized by employing search based optimization techniques [14-16]. The objective F_1 is to optimize the controller parameters by minimizing the performance index J which is given as

$$F_1 = \min(J) \quad (17)$$

where

$$J = \int_0^T (|\Delta V|)dt \quad (18)$$

Where T and ΔV are the simulation time and voltage deviation respectively.

Subject to

$$K_{p,STATCOM}^{min} \le K_{p,STATCOM} \le K_{p,STATCOM}^{max} \quad (19)$$

$$K_{i,STATCOM}^{min} \le K_{i,STATCOM} \le K_{i,STATCOM}^{max} \quad (20)$$

Where K_p and K_i are proportional and integral gains respectively. The ranges of K_p and K_i for STATCOM are given in Table 1 and the parameters of GA [8], PSO [14] and FPA [15, 29] are given in Table 2 respectively.

The simulation block diagram of isolated hybrid energy system for reactive power control using STATCOM and IEEE type-I excitation system is shown in Figure 2. The data used for designing the Isolated Hybrid Energy System is given in the appendix.

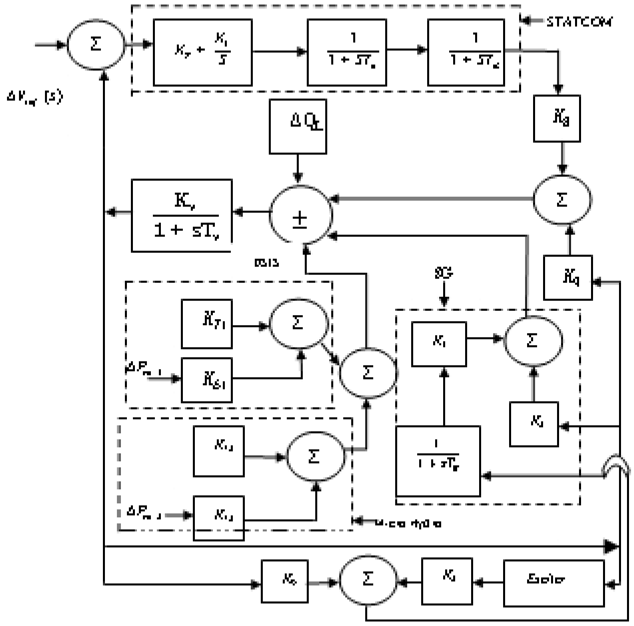


Figure 2. Block Diagram of Isolated Hybrid Energy System

3.1. Flower Pollination Algorithm Structure

FPA based meta-heuristic algorithm is employed to extract the better gain values of P and I in the PI controller in order to minimize the performance index of voltage deviation with respect to the time as given in the section. FPA is a nature inspired evolutionary algorithm and gaining popularity recently for solving nonlinear optimization problems. Xin-She Yang in 2012 proposed the idea of optimization solution structure based on pollination behavior of the flower. Pollination occurs in two ways namely self-pollination and cross-pollination. Self-pollination pollinates the pollen within the same flower or from one flower to another flower in the same plant. Cross-pollination pollinates the pollen with the flower of a different plant. Here the cross-pollination occurring at long distance instigated by the pollinating agents such as bees, bats, birds and flies which could fly a long distance. Behaviors such as jump or fly distance of bees and birds obey a Levy distribution. Based on the pollination process methods, flower constancy and pollination behavior, we can precise the pollination process by following rules:

1. Cross-pollination is considered as Global pollination as the pollination is carried by biotic agents such as bees, birds etc. Also, Levy flights are performed by the biotic agents to carry the pollens over a distance.
2. Self-pollination is considered as local pollination.

3. Reproduction probability is assigned to flower constancy and is proportional to similarity of two flowers involved
4. Local pollination and global pollination are controlled by means of Switching Probability ranges between0 to 1. The characteristics equation of fittest pollination and reproduction is provided as follows

$$x_i^{t+1} = x_i^t + LS(x_i^t - x_{currentbest}) \quad (21)$$

$$LS \sim \frac{\mu\Gamma(\mu)\sin(\pi\mu/2)}{\pi\pi} \frac{1}{st^{1+\mu}}(st>>so>0) \quad (22)$$

Where, $x_i{}^t$ is the selected i[th] pollen in current t[th] population and $x_{currentbest}$ is the best pollen in the current population. LS are the strength of the pollination, which is considering as a stepsize and$x_i{}^{t+1}$ is the i[th] pollen in the t+1 population. Levy flight distribution is used to imitate the characteristic of carrying the pollen over long distance efficiently. Γ(μ) is the standard gamma function, and this distribution is valid for large steps st > 0. In all our simulations, we have used μ = 1.25 and s ∈ [0, 10]. L > 0 is assumed for Levy distribution. The local pollination and flower constancy can be represented as

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \quad (23)$$

Where, x_j^t and x_j^t are pollens from the different flowers of the same plant species. Mathematically, a local random walk if x_j and x_k come from same population or same plant and if we draw 'ε' from a uniform distribution in [0, 1]. So, hence it is confirmed that flower pollination can happen at both local and global search. Proximity probability '*p*' to vary between *p* = 0.5(initially) to 0.8 to balance better pollination over a shortest and longer distance plant. Considering the flower pollination process below steps are incorporated to extract the better gain values (*Kp* & *Ki*) of *P* and *I* in PI controller.

Step 1: Initialize the objective function F1 as mentioned in the equation (17)

Step 2: Initialize a population of *X* (*X1, X2,…Xn*) flowers/pollen gametes with the population size of '*NF x NFPA'*. Where '*NF*' is the Number of flowers as 30 and '*NFPA*' is the dimension size depends on the number of PI controller and the gain value of the respective PI. In this work, three DG's are assumed to be participating. So '*N*' must be the three locations and a size for each DG. For DG variable operational power factor, '*N*' power factors are also randomly created along with the DG sizing.

Step 3: Find the best solution in the initial population

Define a switch probability p ϵ [0, 1]\

While (IT <Maximum Iteration)

For m = 1: NF

If rand < proximity probability(p), Global pollination has been done via equation 21

Else

Draw ε from a uniform distribution in [0, 1]

Randomly choose j[th] and k[th] flower among all the solutions

Do local pollination via equation (23)

End if

Step 4: Evaluate all the solutions for the newly created population using the objective equation (17)

Step 5: If the evaluated new solutions are better, swap the new flowers in the current population

End for

Step 6: Find the best solution in the current population based on the objective fitness equation (17)

End while

4. Results and Discussion

Reactive power compensation of DSTS-micro hydro-diesel based IHPS by STATCOM controller is investigated for the first time. The MATLAB Simulink model was obtained from the transfer function of components used in the hybrid system according to Eq. (2). Optimum K_P and K_I values of PI controller in STACOM are obtained using FPA. System response is obtained with a simulation time of 0.05 s. Hybrid system is tested for different conditions and the time-domain responses were analysed.

4.1. Transient performance analysis of hybrid system without STATCOM under step load disturbance

The dynamic performance of the system without STATCOM is analysed by step change in Q_{Load}. In this paper Q_{Load} increases by 10% of its nominal value (0.075p.u.) at t = 0.01s and 1% of nominal value at t = 0.02s. When the reactive power requirement of the load increases, voltage magnitude of the system varies. Figure 3 shows the voltage deviation corresponding to step changes in Q_{Load}. It has been found that AVR employed with SG is not able to mitigate mismatch in reactive power and reactive power compensating devices are required to stabilise the response.

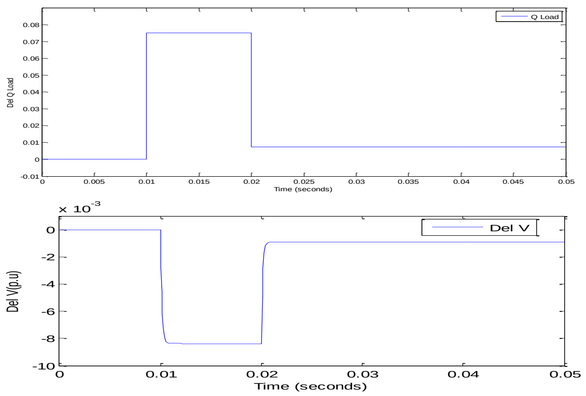


Figure 3. ΔQ_{Load} and ΔV of the system without STATCOM under step disturbances in Q_{Load}

Table 1. Range of Gain values

Variables	Minimum	Maximum
Kp	1	500
Ki	0	15000

4.2. Transient performance of hybrid system with STATCOM under step change in reactive power load:

The model is tested for a 1% step increase in reactive power load demand at t = 0 s. Figure 4.a represents the 1 % step change in reactive power load from its nominal value (i.e. ΔQ_{Load} = 0.0075 pu) at t=0 s. In this case reactive power input to DSTS and micro hydro are maintained constant. Figure4.b represents deviation in terminal voltage at t=0 s corresponding to reactive power demand increase by load. Dynamic response of ΔQ_{IG} , $\Delta Q_{STATCOM}$ and ΔQ_{SG} of the system with STATCOM are shown in Figure.4.c,d,e. Though the input to DSTS and micro hydro remains constant, reactive power observed by IG is also disturbed momentarily as shown in Figure 4. c

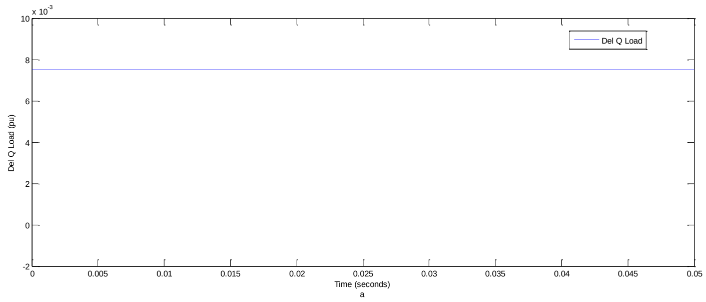
The value of gain constant of PI controller optimized using GA, PSO and FPA for both constant and step change in Q_{LOAD},P_{DSTS} and $P_{micro\ hydro}$ are given in the Table 3. Maximum voltage deviations of transient responses are shown in Table 4. From this it is clear that FPA optimized controllers provide better performance compared to GA and PSO optimized controllers.

Table 2. Parameters of GA, PSO and FPA

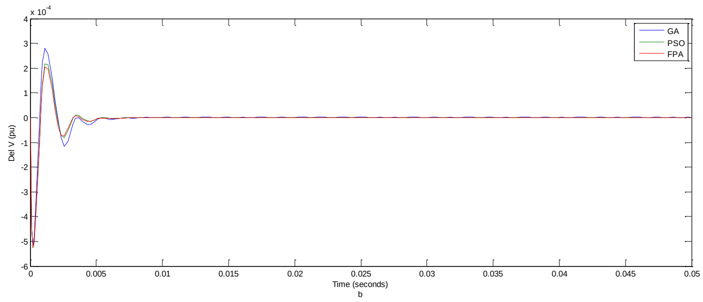
Variables	Minimum	Maximum
Kp	1	500
Ki	0	15000

Table 3. Value of optimized controller gains

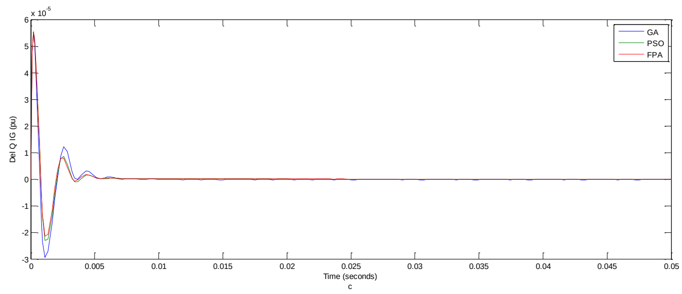
Gains	GA		PSO		FPA	
	Case B	Case C	Case B	Case C	Case B	Case C
$K_{P,STATCOM}$	16.28	17.66	11.27	11.7	9.818	6.9
$K_{I,STATCOM}$	8911.7	9265.9	6736.9	3834.6	5436.8 8	3894.9 7



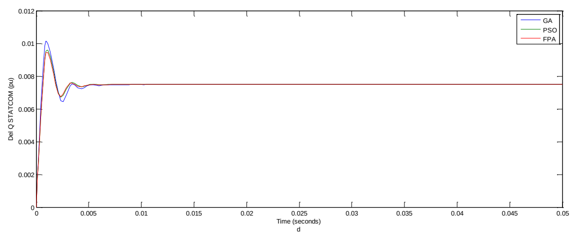
(a) Step change in reactive power to load



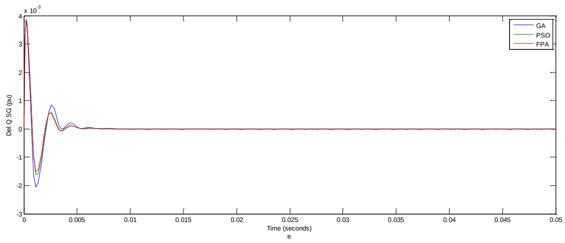
(b) Transient response of ΔV



(c) Transient response of ΔQ_{IG} $(\Delta Q_{DSTS} + \Delta Q_{MicroHydro})$



(d) Transient response of $\Delta Q_{STATCOM}$



(e) Transient response of ΔQ_{SG}

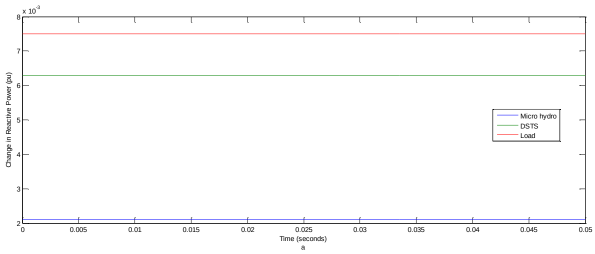
Figure 4. Transient Response of hybrid system for step change in load and constant P_{DSTS} and $P_{MicroHydro}$.

Table 4.Transient response comparison for controllers optimized by GA, PSO and FPA.

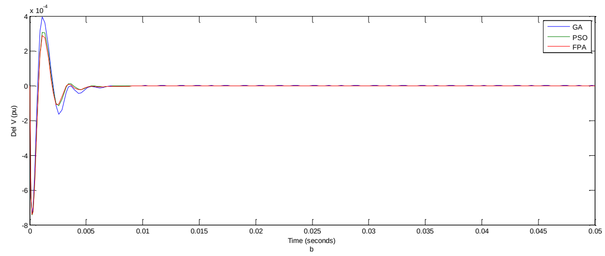
Parameters	Case 4.2			Case 4.3		
	GA	PSO	FPA	GA	PSO	FPA
Voltage Deviation (pu)	0.00026	0.00021	**0.00019**	0.0004	0.00031	**0.00029**
Settling Time (Sec)	0.007	0.0065	**0.0055**	0.0085	0.008	**0.0075**

4.3. Transient performance of hybrid system with STATCOM under step change in reactive power to load, DSTS and micro hydro

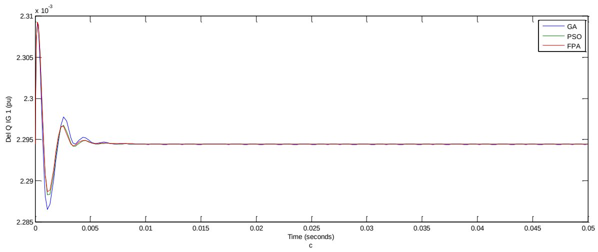
The model is also tested for both 1 % step disturbance in load as well power input to DSTS and micro hydro turbine. For 1 % disturbance in load, DSTS and micro hydro the cumulative change in reactive power is 0.0159 pu as shown in Figure 5.a.



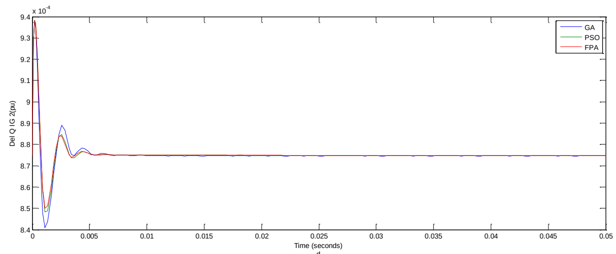
(a) Step change in reactive power to load, DSTS and micro hydro



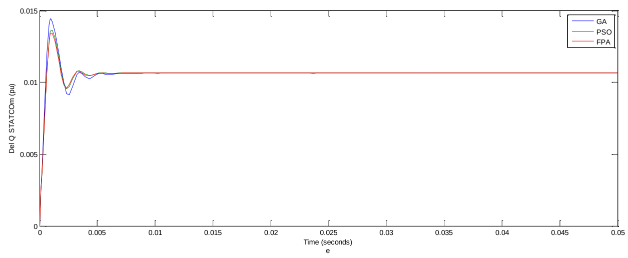
(b) Transient response of ΔV



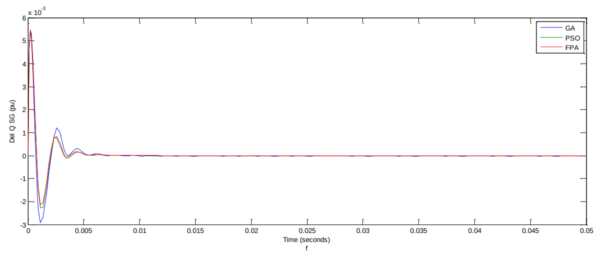
(c) Transient response of $\Delta Q_{IG1} = \Delta Q_{DSTS}$



(d) Transient response of $\Delta Q_{IG2} = \Delta Q_{MicroHydro}$



. (e) Transient response of $\Delta Q_{STATCOM}$



(f) Transient response of ΔQ_{SG}

Figure 5. Transient Response of hybrid system for step change in load,P_{DSTS} and $P_{MicroHydro}$

Mechanical power input to the Induction Generator affects its reactive power requirement as given by (12). $P_{IG1} = P_{DSTS}$ and $P_{IG2} = P_{MicroHydro}$, hence 1% change in its input value at t=0 s causes change in reactive power demand and system terminal voltage decreases resulting in transient. STATCOM and SG acts together to stabilize the system. Figure 5.c, d. e, f shows the dynamic response of ΔQ_{DSTS} ,$\Delta Q_{MicroHydro}$, $\Delta Q_{STATCOM}$ and ΔQ_{SG}.

Appendix gives the data used for designing the IHES. The system transient is high when there is change in both load and input power to Induction Generators as shown in Figure5. b. Initial reactive power requirement by load, DSTS and Micro Hydro are supplied by both SG and STATCOM. As time progress the reactive power requirement is met by STATCOM alone. Increase in number of generation units incorporating Induction Generator reduces the reactive power performance of the system. Optimized PI controller decreases the first peak overshoot and settling time of each component thereby increasing the overall performance of the system.

5. Conclusion

Reactive power control of IG based hybrid system with STATCOM is investigated. From the analysis it is clear that SG alone cannot stabilise the system under varying load condition. Reactive power demand by the system is compensated by both STATCOM and SG. Dynamic response of the system is studied based on reactive power flow balance. Dynamic performance analysis of hybrid system without STATCOM for step change in load has been done. It is clear that voltage deviations are large and AVR employed with SG is not sufficient to stabilize the system. It is concluded that to mitigate the voltage deviation reactive power compensating devices are needed. Reactive power generation through STATCOM depends on PI controller. PI controller in STATCOM is tuned by three different techniques namely GA, PSO and FPA. The performance of the system for three different controller gains were compared. From the transient response it is inferred that FPA tuned controllers provide better response than GA ad PSO tuned controllers.

Appendix

Base power= 300kW
Base voltage=400 V
Generation capacity of DSTS system= 150 kW
Generation capacity of micro hydro system= 50kW
Generation capacity of diesel system = 100kW
DSTS System (IG_1) : P_{IG} = 0.5 pu kW,Q_{IG} = 0.1343 pu kVAR,P_{in} = 0.63 pu kW,η_{IG} = 80%, $r_1 = r_2'$ = 0.19, $x_1 = x_2'$=0.56, $s = -3.49\%$
Micro Hydro System (IG2) : P_{IG} = 0.1667 pu kW , Q_{IG} = 0.042 pu kVAR, P_{in} = 0.21 pu kW, η_{IG} = 80%, $r_1 = r_2'$= 0.55, $x_1 = x_2'$=1.6, $s = -3.37\%$
Diesel System: P_{SG} =0.3333 pu kW, Q_{SG} =0.162 pu kVAR, E_q =1.12418 pu, δ =17.2483°, E_q' =0.9804 pu, V =1.0 pu, x_d = 1.0 pu, x_d'=0.15 pu, T_{do}' =5.0 s
STATCOM: $Q_{COM=}$0.7646 pu kVAR, α_o =53.314° , V_{dc} =256 V, L_{ac} =0.3037 mH, V =1.0 pu.

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