Control Strategies for a Grid-Connected Hybrid Energy System

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***Abstract*—This paper presents the control strategies to operate a grid connected hybrid system. The hybrid system consists of a Photovoltaic (PV) array and a Proton Exchange Membrane Fuel cell (PEMFC). Due to the intermittent nature of the solar energy the PV array becomes uncontrollable in delivering maximum power to the load. In coordination with the PEMFC the hybrid system output power becomes controllable. The coordination of the two control modes Unit Power Control (UPC) mode and feeder-flow control (FFC) mode can be applied to the system. In UPC mode the DGs regulate the voltage magnitude at the connection point where source power is injected. In this mode if a load increases anywhere in the micro-grid the extra power comes from the grid, since the hybrid source regulates power output to a constant. In FFC mode the DGs regulate the voltage magnitude at the connection point and the power flowing in the feeder. In FFC mode extra load demands are picked up by the DGs which maintain a constant load from utility point of view. The proposed control strategies always operate the PV array at the maximum output power and the PEMFC at its high efficiency band improving the performance of the system operation with reduced number of mode changes.**

***Index Terms*— Fuel cell, Distributed generation, Photovoltaic Cell, Hybrid system, MicroGrid.**

INTRODUCTION

IN terms of currently available technologies, the distributed generation includes fuel cells, renewable generation sources such as wind or solar PV systems, micro turbines and inverter based internal combustion generators. PV energy is an important renewable technology that requires an inverter to interface with the electrical distribution system. The major issue with this technology is the nature of the generation. The availability of energy is driven by weather and cell temperature but not on the loads of the systems [1]. Because of the intermittent nature of PV array it becomes an uncontrollable source. To overcome these demerits, alternative sources, such as fuel cell [2] should be connected in the hybrid system. By changing the fuel cell output power, the hybrid source output can be controlled. However, PEMFC works only at a high efficiency point within a specific power range.

The hybrid energy source can either be connected to the main grid or work independent with respect to the grid-connected mode or islanded mode respectively. In the grid-connected mode, the hybrid system is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. When load demand changes, the power supplied by the main grid and hybrid system must be properly changed. The power delivered from the PV array, PEM fuel cell and main grid must be coordinated to meet load demand. The hybrid system is operated in two modes:

1) unit-power control (UPC) mode and feeder-flow control (FFC) mode [8][9]. In the UPC mode, if there is any increase in the load that will be compensated by the main grid, since the hybrid source output is regulated to reference power. Therefore, the reference value of the hybrid source output P^{ref}_{MS} must be determined. In FFC mode, extra load is picked up by the hybrid source and feeder flow is regulated to constant and hence the feeder reference power P_{feeder}^{ref} must be known.

The proposed control strategy is to coordinate the two control modes and determine the reference values of the UPC and FFC modes so that all constraints are satisfied.

SYSTEM MODELING

A. *Structure of Grid-connected Hybrid Energy System*

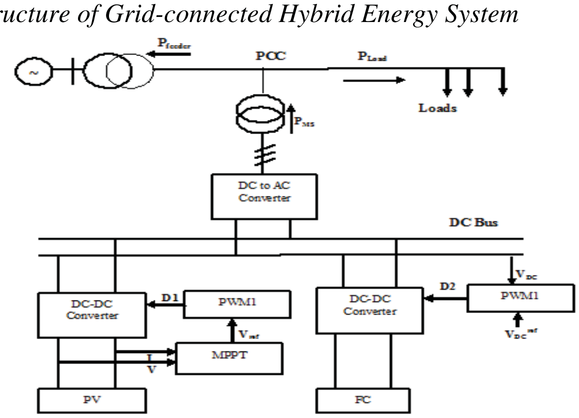

Fig-1 Grid connected PV-FC Hybrid energy system

The hybrid source consists of a PV-FC with the main grid connecting to loads at the Point of Common Coupling as shown in Figure.1. The photovoltaic [1] and the PEMFC [2] are modeled as nonlinear voltage sources. These sources are connected to dc–dc converters which are coupled at the dc side of a dc/ac inverter.

B. Proton Exchange Membrane Fuel Cell Model

Proton Exchange Membrane (PEM) fuel cells show great promise for use as distributed generation (DG) sources. Compared with other DG technologies, such as wind and photovoltaic (PV) generation, PEM fuel cells have the advantage that they can be placed at any site in a distribution system, without geographic limitations, to achieve the best performance. The overall reaction in a PEM fuel cell can be simply written as

$$H_2 + \frac{1}{2} O_2 = H_2O$$

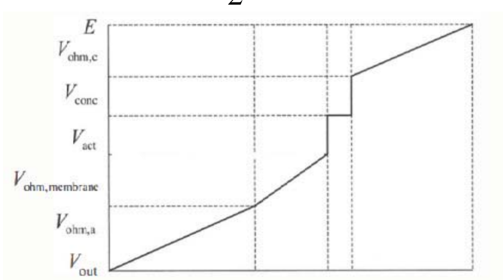

Fig.2. PEMFC voltage drops

The PEMFC output voltage [5] is given from fig.2. as

$$V_{out} = E_{Nerst} - V_{act} - V_{ohm} - V_{conc} \qquad (1)$$

Where E_{Nerst} is the "thermodynamic potential" of Nerst, which represents the reversible (or open-circuit) voltage of the fuel cell. Activation voltage drop is given in the Tafel equation as

$$V_{act} = T[a + b\ln(I)] \qquad (2)$$

Where a,b are the constant terms in the Tafel equation (in volts per Kelvin).

The overall ohmic voltage drop is given by

$$V_{ohm} = IR_{ohm} \qquad (3)$$

The ohmic resistance of PEMFC consists of the resistance of the polymer membrane and electrodes, and the resistances of the electrodes.

The concentration voltage drop is given as

$$V_{conc} = -\frac{RT}{zF}\ln\left(1 - \frac{I}{I_{limit}}\right) \qquad (4)$$

C. PV Array Model

The simplified equivalent circuit shown in Fig (3) is of a solar cell consists of a diode and a current source connected in parallel with a series resistance R_s which represents the material resistivity and ohmic losses due to levels of contact. The current source produces the photocurrent I_{Ph}, which is directly proportional to solar irradiance G.

The mathematical model [3] of PV cell can be expressed as

$$I_{pv} = I_{Ph} - I_0\left[\exp q\left(\frac{V_{pv} + I_{pv}.R_s}{AKT}\right) - 1\right] \qquad (5)$$

Since Photocurrent I_{Ph} is directly proportional to solar radiation G

$$I_{Ph}(G) = I_{sc}\frac{G}{G_{ref}} \qquad (6)$$

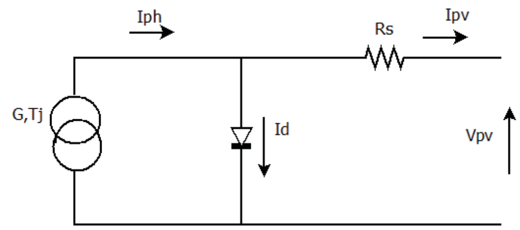

Fig.3. Simplified equivalent solar cell model with R_s

The short-circuit current I_{SC} of solar cell depends linearly on cell temperature

$$I_{sc}(T_j) = I_{scs}\left[1 + \Delta I_{sc}(T_j - T_{jref})\right] \qquad (7)$$

Thus, I_{Ph} depends on solar irradiance and cell temperature

$$I_{Ph}(G, T_j) = I_{scs}\frac{G}{G_{ref}}\left[1 + \Delta I_{sc}(T_j - T_{jref})\right] \qquad (8)$$

I_0 also depends on solar irradiation and cell temperature and can be mathematically given as

$$I_0(G, T_j) = \frac{I_{Ph}(G, T_j)}{e\left(\frac{V_{oc}(T_j)}{V_t(T_j)}\right) - 1} \qquad (9)$$

D. MPPT Control

Even though there are many Maximum Power Point Tracking algorithms proposed in the literature the perturbation and observation (P&O) is used in this paper as it is the most widely used method. A feedback loop and few measures are needed. The panel voltage is deliberately perturbed (increased or decreased) then the power is compared to the power obtained before to disturbance. Specifically, if the power panel is increased due to the disturbance, the following disturbance will be made in the same direction. And if the power decreases, the new perturbation is made in the opposite direction. The P&O MPPT algorithm with a power-feedback control is given below. As. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref} .

Perturbation and Observation MPPT Algorithm:

Step1: Read voltage and current samples V(k), I(k), V(k+1),I(k+1)

Step 2: Calculate P(k) and P(k+1)

Step 3: Return ΔV_{ref} =0 if P(k)- P(k+1)=0

Step 4: Check if P(k) - P(k+1)>0

If yes

(a) Return ΔV_{ref}=C if V k) - V(k+1)>0 else ΔV_{ref}=-C

If no

(b) Return ΔV_{ref}=-C if V k) - V(k+1)>0 else ΔV_{ref}=C

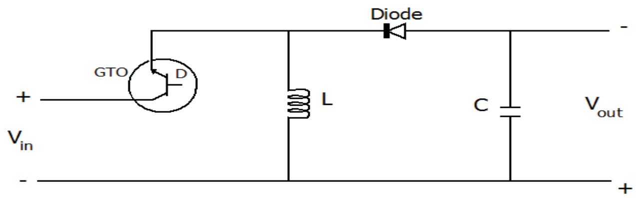

Fig. 4. Buck-Boost topology

The buck-boost converter shown in fig.4 consists of one switching device (GTO) that enables it to turn on and off depending on the applied gate signal D. The gate signal for the GTO can be obtained by comparing the saw tooth waveform with the control voltage [3]. The change of the reference voltage ΔV_{ref} obtained by MPPT algorithm becomes the input of the pulse width modulation (PWM).

III CONTROL STRATEGY OF THE HYBRID SYSTEM

As mentioned before, the purpose of the operating algorithm is to determine the control mode of the hybrid source and the reference value for each control mode so that the PV is able to work at maximum output power and the constraints are fulfilled. Once the constraints (P_{FC}^{low}, P_{FC}^{up} & P_F^{max}) are known, the control mode of the hybrid source (UPC mode and FFC mode) depends on load variations and the PV output. The control mode is decided by the algorithm. In the UPC mode, the reference output power of the hybrid source depends on the PV output and the constraints of the FC output.

A. Control Strategy in UPC Mode

In this part, the proposed algorithm determines the hybrid source works in the UPC mode. This algorithm allows the PV to work at its maximum power point, and the FC to work within its high efficiency band. In the UPC mode, the hybrid source regulates the output to the reference value. Then

$$P_{PV} + P_{FC} = P_{MS}^{ref} \qquad (10)$$

Equation (10) shows that the variations of the PV output will be compensated for by the FC power and, thus, the total power will be regulated to the reference value. Table 1 describes the operation strategy of the hybrid source in UPC mode. The algorithm includes two areas: Area 1 and Area 2. In Area 1,if P_{PV} is less than P_{PV1} , and then the reference power is set at where

$$P_{PV1} = P_{FC}^{up} - P_{FC}^{low} \qquad (11)$$

$$P_{MS1}^{ref} = P_{FC}^{up} \qquad (12)$$

If PV output is zero, then (10) deduces to be equal to P_{FC}^{up}. If the PV output increases to, then from (10) and (11), we obtain P_{FC} equal to P_{FC}^{low} . In other words, when the PV output varies from zero to P_{PV1}, the FC output will change from P_{FC}^{up} to P_{FC}^{low}. As a result, the constraints for the FC output always reach Area 1.

Area 2 is for the case in which PV output power is greater than P_{PV1}. As depicted in table 1 if PV output is larger than P_{PV1}, the reference power will be increased by the amount of ΔP_{MS}, and we obtain

$$P_{MS2}^{ref} = P_{MS1}^{ref} + \Delta P_{MS} \qquad (13)$$

Similarly, if P_{PV} is greater than P_{PV2} than, the FC output becomes less than its lower limit and the reference power will be thus increased by the amount of ΔP_{MS}. In other words, the reference power remains unchanged and equal to P_{MS2}^{ref} if P_{PV} is less than P_{PV2} and greater than P_{PV1} where

$$P_{PV2} = P_{PV1} + \Delta P_{MS} \qquad (14)$$

it is noted that ΔP_{MS} is limited so that with the new reference power, the FC output must be less than its upper limit P_{FC}^{up} . Then, we have

$$\Delta P_{MS} \le P_{FC}^{up} - P_{FC}^{low} \qquad (15)$$

In general, if the PV output is between and, then we have

$$P_{MS\,i} = P_{MS\,i-1}^{ref} + \Delta P_{MS} \qquad (16)$$

$$P_{PV\,i} = P_{PV\,i-1}^{ref} + \Delta P_{MS} \qquad (17)$$

Equations (16) and (17) show the method of finding the reference power when the PV output is in Area 2. The relationship between $P_{MS\,i}$ and P_{PVi} is obtained by using (11), (12) and (17) in (16), and then

$$P_{MSi}^{ref} = P_{Pvi} + P_{FC}^{min}, \; i=2,3,4\ldots., \qquad (18)$$

The determination of in Area 1 and Area 2 can be generalized by starting the index from 1. Therefore, if the PV output is $P_{PV\,i-1} \le P_{PV} \le P_{PV\,i}$

then we have

$$P_{PVi} = P_{PVi-1} + \Delta P_{MS} \; i=1,2,3,4,.... \qquad (19)$$

it is noted that when is given in (11), and

$$P_{PVi-1} = P_{PV0} = 0 \qquad (20)$$

In brief, the reference power of the hybrid source is determined according to the PV output power. If the PV output is in Area 1, the reference power will always be constant and set at P_{FC}^{up}. Otherwise, the reference value will be changed by the amount of ΔP_{MS}, according to the change of PV power. The reference power of the hybrid source P_{MS}^{ref} in Area 1 and Area 2 is determined by (19) and (20). P_{PV0}, P_{PV1}, and ΔP_{MS} are shown in (20), (11), and (15), respectively. The unit power control algorithm for determining the reference power is given below. The constant must satisfy (15). If C increases the number of change P_{MS}^{ref} will decrease and thus the performance of system operation will be improved.

Table 1

Operating strategy for hybrid source in UPC mode

Area-2	P_{PVn}	$P_{MSn}^{ref} = P_{MSn-1}^{ref} + \Delta P_{MS}$	ΔP_{MS}
	. . .		. . .
	P_{PVi}	$P_{MSi}^{ref} = P_{MSi-1}^{ref} + \Delta P_{HS}$	ΔP_{MS}
	. . .	:	. . .
	P_{PV3}	$P_{MS3}^{ref} = P_{MS2}^{ref} + \Delta P_{MS}$	ΔP_{MS}
	P_{PV2}	$P_{MS2}^{ref} = P_{MS1}^{ref} + \Delta P_{MS}$	ΔP_{MS}
	P_{PV1}	$P_{MS1}^{ref} = P_{FC}^{max}$	ΔP_{MS}
Area-1	$P_{PV} = 0$	P_{FC}^{low}	

Unit Power Control Algorithm:

1. Initialize the values $P_{MS}^{ref} = P_{fc}^{max}$ & $\Delta P_{MS}=0$
2. Calculate $P_{MS}^{ref}(new) = P_{MS}^{ref}(old) + \Delta P_{MS}$
3. Check for $P_{PV} > P_{PV1}$ & $P_{FC} \le P_{FC}^{min}$
   If yes return $\Delta P_{MS}=+C$ else return $\Delta P_{MS}=0$
4. Check for $P_{FC} \ge P_{FC}^{max}$
   If yes return $\Delta P_{MS}=+C$ else return $\Delta P_{MS}=0$

To improve the performance of the algorithm, a hysteresis is included in the simulation model. The hysteresis is used to prevent oscillation of the setting value of the hybrid system reference power.

B. Overall Control Strategy of the Grid Connected Hybrid Energy System

In this part, a control strategy is presented to coordinate the two operating controls. The purpose of the algorithm is to decide when each control mode is applied and to determine the reference value of the feeder flow when the FFC mode is used. If the hybrid source works in the UPC mode, the hybrid output is regulated to a reference value and the variations in load are matched by feeder power. On the other hand, when the hybrid works in the FFC mode, the feeder flow is controlled to a reference value P_{feeder}^{ref} and, thus, the hybrid source will compensate for the load variations

If load is in Area I, the UPC mode is selected. Otherwise, the FFC mode is applied with respect to Area II. In the UPC area, the hybrid source output is P_{MS}^{ref}. If the load is lower than the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand.

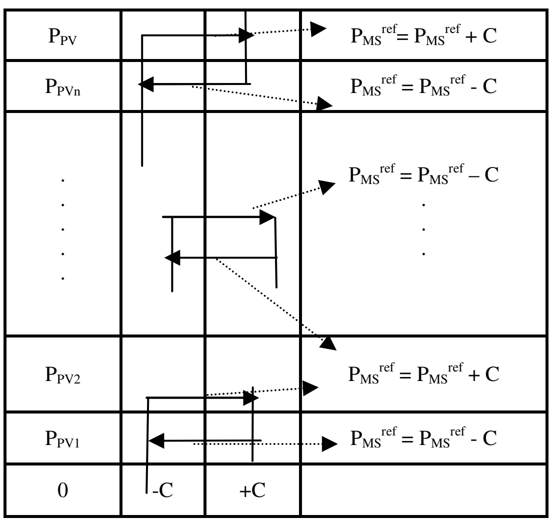

Fig.5. Hysteresis control scheme for PMS(ref) control.

Table 2

Overall operating strategy for a grid – connected hybrid system

P_{load}^{max}	Area-II (FFC)	Load Shedding			$P_{FC}^{max} - P_{FC}^{up}$
P_{load2}		FC	$P_{FC}^{up} - P_{FC}$		
P_{load1}	Area-I (UPC)	Feeder		P_{feeder}^{max}	
P_{MS}^{ref}		PV		P_{PV}	
0		FC		P_{FC}	

In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area II is

$$P_{Load1}=P_{Feeder}^{max}+P_{MS}^{ref} \quad (21)$$

When the mode changes to FFC, the feeder flow reference must be determined

$$P_{Feeder}^{ref}=P_{Feeder}^{max} \quad (22)$$

In the FFC area, the variation in load is matched by the hybrid source. If the FC output increases to its upper limit and the load is higher than the total generating power, then load shedding will occur. The limit that load shedding will be reached is

$$P_{Load2}=P_{FC}^{up}+P_{Feeder}^{max}+P_{PV} \quad (23)$$

Equation (23) shows that is minimal when PV output is at 0kW. Then

$$P_{Load2}^{min}=P_{FC}^{up}+P_{Feeder}^{max} \quad (24)$$

Equation (24) means that if load demand is less than, load shedding will never occur. From the beginning, FC has always worked in the high efficiency band and FC output has been less than. If the load is less than, load shedding is ensured not to occur. However, in severe conditions, FC should mobilize its availability, to supply the load. Thus, the load can be higher and the largest load is

$$P_{Load}^{max}=P_{FC}^{max}+P_{Feeder}^{max} \quad (25)$$

$$P_{Area-II}=P_{FC}^{max}-P_{FC}^{up} \quad (26)$$

Table 3 System Parameters

Parameters	Value
P_{FC}^{low}	0.01 MW
P_{FC}^{up}	0.07 MW
P_{Feeder}^{max}	0.01 MW
ΔP_{MS}	0.03 MW

IV SIMULATION RESULTS

The proposed control schemes were implemented to the system model shown in Fig.1 using MATLAB/SIMULINK environment with the system parameters given in Table3 and the performance is analyzed.

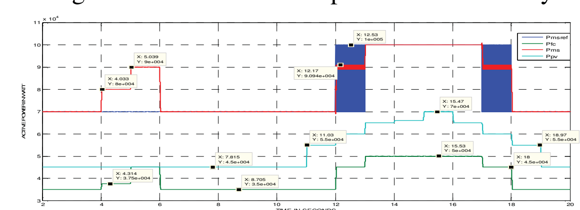

Figure 6 - Operating strategy of the hybrid source without hysteresis

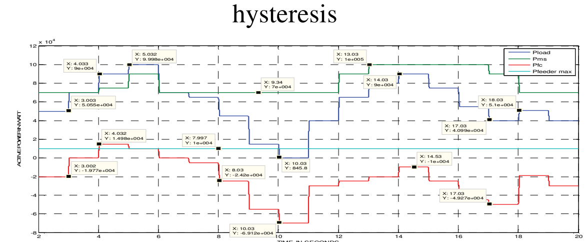

Figure 7 Simulation result without hysteresis - Operating strategy of the whole system

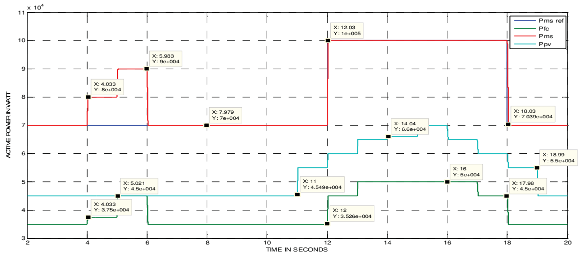

Figure 8 Improving operating performance by using hysteresis - Operating strategy of the hybrid source

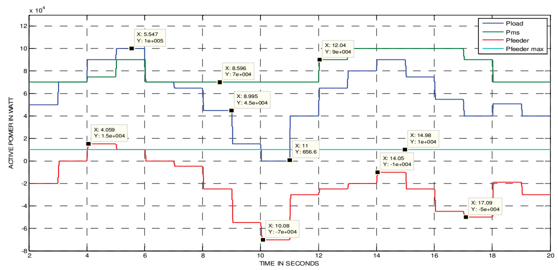

Figure 9 Improving operating performance by using hysteresis - Operating strategy of the whole system

Following tables gives the detailed analysis of the system operation with and without hysteresis control scheme.Table4 Operating strategy of hybrid source without hysteresis System operation in FFC mode from 4 seconds to 6 seconds which is highlighted in dark red color in Table 4 and Table 5. Operation without hysteresis controller is highlighted in dark blue colour in Table4 which is eliminated using hysteresis controller (Table5).

Table 4. Operating strategy of hybrid source without hysteresis

Time in Seconds		Pms_ref in MW	Pms in MW	Ppv in MW	Pfc in MW
From	To				
2	4	0.07	(0.07, 0.08)	0.045	(0.035, 0.0355)
4	6	0.07	(0.08, 0.09, 0.07)	0.045	(0.0355, 0.045, 0.035)
6	8	0.07	0.07	0.045	0.035
8	10	0.07	0.07	0.045	0.035
10	12	0.07	(0.07, 0.09)	(0.045, 0.055, 0.06)	(0.035, 0.045)
12	13	(0.07,0.1)	(0.09, 0.1)	0.06	(0.045, 0.05)
13	14	0.1	0.1	(0.06, 0.065, 0.066)	0.05
14	16	0.1	0.1	(0.066, 0.07, 0.065)	0.05
16	17	0.1	(0.1, 0.09)	(0.065,0.06)	(0.05, 0.045)
17	18	(0.1, 0.07)	(0.09, 0.07)	(0.06, 0.055)	(0.045, 0.035)
18	20	0.07	0.07	(0.055,0.045)	0.035

V CONCLUSION

A hybrid system comprising a PV array and PEMFC is considered. The operating strategy of the system is based on the UPC mode and FFC mode. The purpose of the proposed operating strategy presented in this paper is to determine the control mode to minimize the number of mode changes, to operate PV at the maximum power point and to operate the FC output at its high-efficiency performance band. The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and thus the hybrid source results in a stable operation. The changes in operating mode occur only when the load demand is at the boundary of mode change (P_{load1}); otherwise the operating mode is either UPC mode or FFC mode. Besides the variation of hybrid source reference power is eliminated by means of hysteresis. In addition the number of mode changes is reduced and hence the system works more stably.

Table 5 Operating strategy of hybrid source with hysteresis

Time in Seconds		Pms_ref in MW	Pms in MW	Ppv in MW	Pfc in MW
From	To				
2	4	0.07	(0.07, 0.08)	0.045	(0.035, 0.0355)
4	6	0.07	(0.08, 0.09, 0.07)	0.045	(0.0355, 0.045, 0.035)
6	8	0.07	0.07	0.045	0.035
8	10	0.07	0.07	0.045	0.035
10	12	0.07	(0.07, 0.09)	(0.045, 0.055, 0.06)	(0.035, 0.045)
12	14	0.1	(0.09, 0.1)	(0.06,0.065, 0.066)	(0.045, 0.05)
14	16	0.1	0.1	(0.066, 0.07, 0.065)	0.05
16	18	0.1	(0.1, 0.09, 0.07)	(0.065,0.06, 0.055)	(0.05, 0.045, 0.035)
18	20	0.07	0.07	(0.055,0.045)	0.035

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