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Design and Analysis of 1.4 MW Hybrid Saps System for Rural Electrification in Off-Grid Applications

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Abstract**—**In this paper, optimal design of hybrid standalone power supply system (SAPS) is done for off grid applications in remote areas where transmission of power is difficult. The hybrid SAPS system uses two primary energy sources, wind and solar, and in addition to these diesel generator is also connected to meet the load demand in case of failure of wind and solar system. This paper presents mathematical modeling of 1.4 MW hybrid SAPS system for rural electrification. This paper firstly focuses on mathematical modeling of PV module connected in a string, secondly focuses on modeling of permanent magnet wind turbine generator (PMWTG). The hybrid controller is also designed for selection of power from the source available as per the load demand. The power output of hybrid SAPS system is analyzed for meeting load demands at urban as well as for rural areas.

Keywords**—**SAPS, DG, PMWTG, rural area, off grid, PV module.

I. INTRODUCTION

A Stand Alone Power Supply (SAPS) system consists of combination of energy sources such as wind, solar, fuel cell. These natural sources are combined together to achieve discontinuous supply of energy to be converted to electricity. In rural areas, system installed is based on specific energy requirements as per the load demand and the renewable energy resources available [1]. To use solar and wind energy resources more efficiently and economically, it is of great importance to optimize the size of hybrid PV/wind system with battery bank or DG. The sizing optimization method insures the lowest investment with a reasonable and full use of the off-grid system. In this way, the system can work at the optimum conditions with optimal configurations in terms of investment and reliability requirement of the demand [2]. The erratic nature of solar and wind makes the system unreliable. The utilization of these two renewable energy sources together enhances the power transfer efficiency and reliability of the system. It is called hybrid energy system. In this system, when one source is not enough to meet the load demand, the other energy source overcomes [3].

II. SYSTEM CONFIGURATION

The PV module we are designing for SAPS system is of power rating 1 MW. For achieving 1 MW power through solar panel PV module, 200 Watts rated panel is combined in a string. As the power rating is increased, the conversion efficiency is also increased. The WIND module designed for SAPS system is of power rating 0.4 MW. Thus, the total capacity of hybrid SAPS is 1.4 MW. The electrical ratings are mentioned in Table I.

The electrical specifications are under test conditions of irradiance of 1 kW/m^2, spectrum of 1.5 air masses and cell temperature of 25 °C. Hybrid SAPS power plant consists of mainly the solar cells, wind & DG. The energy is produced from the combination and is fed to the load via hybrid controller; the function of hybrid controller is to allow the energy sources to supply the load separately or simultaneously depending on the availability of the energy sources. The functional block diagram of solar-wind hybrid power plant is shown in Fig. 1.

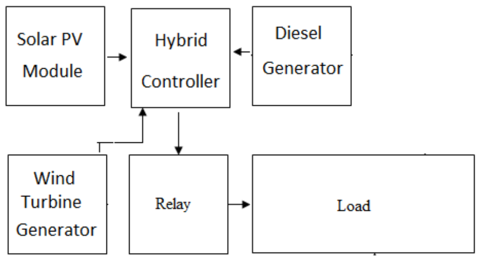

Fig. 1 Functional Block Diagram of SAPS system

III. MATHEMATICAL MODELING OF SAPS SYSTEM

Modeling of PV

The solar PV array includes six modules and each module has six solar cells connected in series. The proposed model of solar PV array is given in Fig. 2. The voltage and current charters tics equation of solar cell is provided as [4], [6].

Module Photo-Current Iph

$$Iph = [I_{sc} + Ki(T - 298)] \times \frac{Ir}{1000Iph} = [I_{sc} + Ki(T - 298) \times Ir/1000] \quad (1)$$

Here, Iph: photo-current (A); Isc: short circuit current (A); Ki: short-circuit current of cell at 25 °C and 1000 W/m^2; T: operating temperature (K); Ir: solar irradiation (W/m^2).

Module Reverse Saturation Current Irs

$$I_{rs} = \frac{I_{sc}}{\left[exp\left(\frac{qVOC}{NSknT}\right)-1\right]I_{rs}} = I_{sc}/\left[exp\left(\frac{qVOC}{NSknT}\right) - 1\right] \quad (2)$$

Here, q: electron charge, = 1.6 × 10−19C; Voc: open circuit voltage (V); Ns: number of cells connected in series; n: the ideality factor of the diode; k: Boltzmann's constant, =

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1.3805 × 10−23 J/K.

TABLE I
IEEE STANDARD ELECTRICAL RATINGS FOR PV MODULE & WIND

Specification of PV Module			Specification of Wind Turbine			
1	Power Rating	P=200 W	1.	Rated Power	10 KW at 11 m/s (25 mph)	3 blade up wind
2	Voltage at maximum power	V(Pmax)=35.16 V	2.	Rated Annual Energy	13600 Kwh at 5 m/s (11 mph)	None, fixed pitch
3	Short circuit current	Isc=5.92 A	3.	Max. Design wind speed	60 m/s (134 mph)	240 V Ac 1phase 50 HZ
4	Open circuit voltage	Voc=43.75 V	4.	Cut in wind speed	2.2 m/s (5 mph)	-40 to +60 °C
5	Operating voltage	V(operating)=24 V	5.	Nominal Power	10 Kw at 12 m/s (27 mph)	Permanent magnet alternator

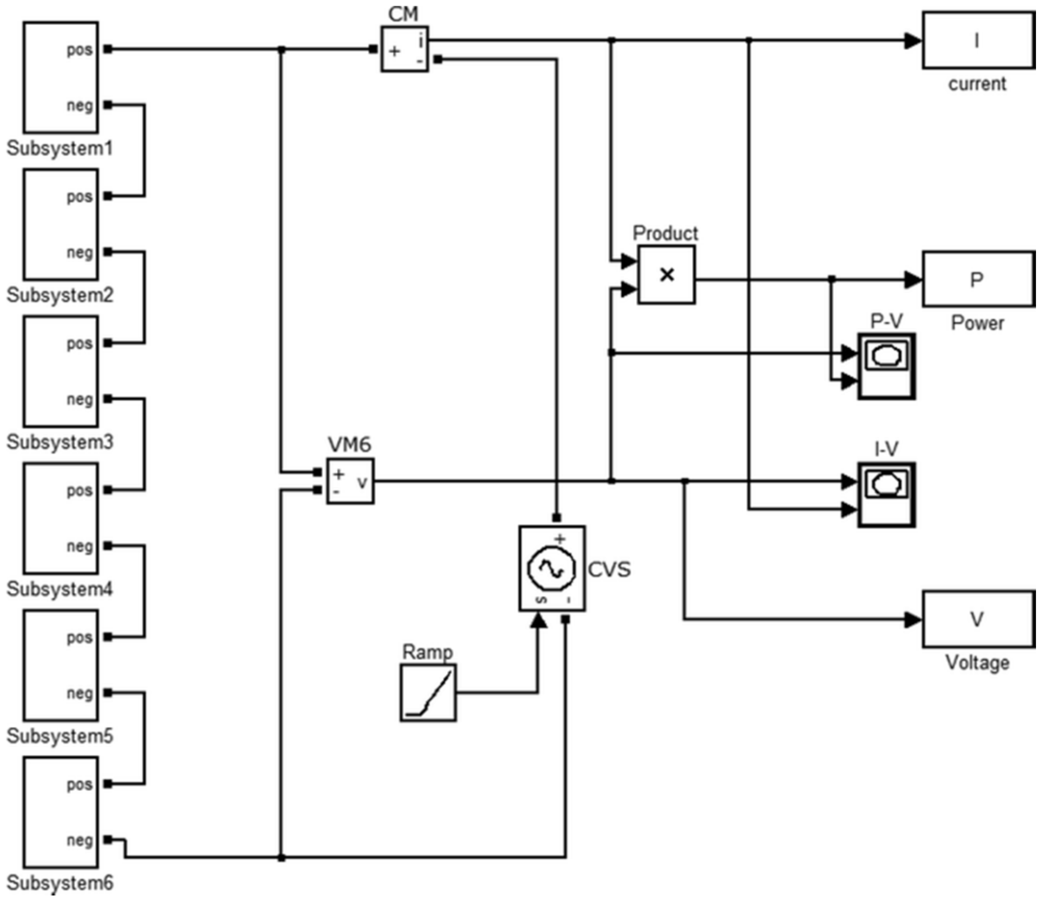

Fig. 2 Proposed model of solar PV

The module saturation current I0 varies with the cell temperature, which is given by:

$$I0 = I_{rs}[TTr]3exp[q \times Eg0nk(1T - 1Tr)I_0 = I_{rs}[TTr]3exp[q \times Eg0nk(1T - 1Tr)]] \quad (3)$$

Here, Tr: nominal temperature = 298.15 K; Eg: band gap energy of the semiconductor, = 1.1 eV.

The current output of PV module is:

$$\mathrm{i} = \mathrm{NP} \times \mathrm{I_{ph}} - NP \times \mathrm{I_0} \times \left[\exp\left(\frac{\mathrm{V}}{\mathrm{NS}} + \mathrm{I} \times \frac{\mathrm{R_s}}{\mathrm{NP_n}} \times \mathrm{V_t}\right) - 1\right] - \mathrm{I_s h_I} = \mathrm{NP} \times \mathrm{Iph} - \mathrm{NP} \times \mathrm{I_0} \times \left[\exp\left(\frac{\mathrm{V}}{\mathrm{NS}} + \mathrm{I} \times \frac{\mathrm{R_s}}{\mathrm{NP_n}} \times \mathrm{V_t}\right) - 1\right] - \mathrm{Ish} \quad (4)$$

with

$$V_t = k \times T_q V_t = k \times T_q \quad (5)$$

and

$$\mathrm{Ish} = \mathrm{V} \times \mathrm{NP/NS} + \mathrm{I} \times \mathrm{RSRshIsh} = \mathrm{V} \times \mathrm{NP/NS} + \mathrm{I} \times \mathrm{RSRsh} \quad (6)$$

Here: Np: number of PV modules connected in parallel; Rs: series resistance (Ω); Rsh: shunt resistance (Ω); Vt: diode thermal voltage (V).

The input parameters for modeling: Tr is reference temperature = 298.15 K; n is ideality factor = 1.2; k is Boltzmann constant = 1.3805 × 10−23 J/K; q is electron charge = 1.6 × 10−19; Isc is PV module short circuit current at 25 °C and 1000 W/m^2 = 6.11 A; Voc is PV module open circuit voltage at 25 °C and 1000 W/m^2 = 0.6 V; Eg0 is the band gap energy for silicon = 1.1 eV. Rs is series resistor, normally the value of this one is very small, = 0.0001 Ω; Rsh is shunt resistor, the value of this is so large = 1000 Ω.

Module photon-current is given in (1) and modeled as Fig. 4

(Ir0 = 1000 W/m^2).

$$I_{ph} = \frac{[I_{sc}+K_i(T-298)\times]I_r}{1000I_{ph}} = [I_{sc} + K_i(T - 29i8] \times I_r/1000 \quad (7)$$

Modeling of PMSG

In order to develop the mathematical model for a PMSG, it is essential to make the following assumptions [5]:

- The conductivity of the permanent magnet is zero
- Saturation is neglected
- Induced electromotive force (EMF) is sinusoidal
- Eddy currents and hysteresis losses are negligible
- There are no field current dynamics

With the assumptions above, the wind turbine causes the rotor of the PMSG to rotate.

This can be represented in the direct-quadrature (DQ) coordinate system, which is described as:

$$V_{qs} = -r_s i_{qs} + L_{qs}\frac{d}{dt}i_{qs} - \omega_r L_{ds} i_{ds} + \omega_r \frac{dy}{dx}\psi d_s$$

$$V_{ds} = -= -r_s i_{ds} + L_{ds}\frac{d}{dt}i_{ds} + \omega_r L_{ds} i_{ds}$$

where *Vqs* is the quadrature-axis (q-axis) stator terminal voltage in *volt*. *Vds* is the direct-axis (d-axis) stator terminal voltage in *volt*. *ids* is the d-axis stator current in ampere *A*. *iqs* is the q-axis stator current in ampere *A*.. *ωr* is the angular velocity of generator rotor in *rad/sec*. *rs* is the equivalent resistance of the stator winding. *Lds* is the stator equivalent inductance in d-axis. *Lqs* is the stator equivalent inductance in q-axis. $\frac{d}{dt}\psi ds$ is the amplitude of the flux linkages in *v/rad/sec*.

In the rotor reference frame, the electromagnetic torque can be described by

$$T_e = \frac{3P}{4}\left[i_{ds} i_{qs}(L_{ds} - L_{qs}) + i_{qs}\frac{d}{dt}\psi ds\right]$$

where, *Te* is electromagnetic torque in *Nm*. *P* is the pole number of generator stator.

The relationship between the angular velocity of the generator rotor and the mechanical angular velocity of the wind turbine rotor is given as

$$\omega = 2\omega_r/PG$$

$$\frac{d}{dt}\omega_r = \frac{P}{2j}(T_m - T_e)$$

where, *G* is the gear ratio. *Tm* is the input torque to the generator rotor in *Nm*. *J* is the inertia of the generator rotor in *kgm2*.

The input torque to the generator can be obtained by means of the torque of wind turbine rotor divided by the gear ratio

$$T_m = \frac{T_t}{G}$$

Here it is assumed that the torque loss through the mechanical transmission system is neglected. For a direct-driven PMSG wind turbine, *G*=1, and *Tm* = *Tt*.

Mathematical Inverse Parks and Clarke Transformation

The discussion above is based on the rotating reference frame. A practical generator produces 3-phase AC power. For this reason, the inverse Park and Clarke transforms are introduced to implement the 3-phase AC output from the generator model.

As Fig. 3 shows, the transform from the stator axis reference frame (αβ) to the rotating reference frame (dq) is called the Park transform. The Clarke transform is the transformation of the 3-phase reference frame to the 2-phase orthogonal stator axis (αβ).

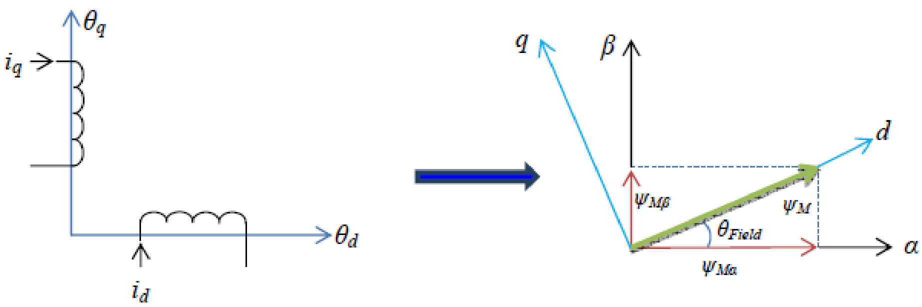

Fig. 3 Inverse Park transform

As Fig. 3 assumes the αβ frame has an angle θ field with the dq frame, the inverse Park transform (dq - αβ) can be expressed as:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \begin{bmatrix}cos\theta_{field} & -sin\theta_{field}\\ sin\theta_{field} & sin\theta_{field}\end{bmatrix}\begin{bmatrix}d\\ q\end{bmatrix}$$

The mathematical inverse Clarke transform is given as:

$$\begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix} = \begin{bmatrix}1 & 0\\ -1/2 & \sqrt{3}/2\\ -1/2 & -\sqrt{3}/2\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix}$$

In order to simulate the power generation from the wind turbine, it is necessary to model the wind and obtain the power coefficient of the wind turbine rotor using MATLAB. Fig. 4 shows the modeling of PMSG.

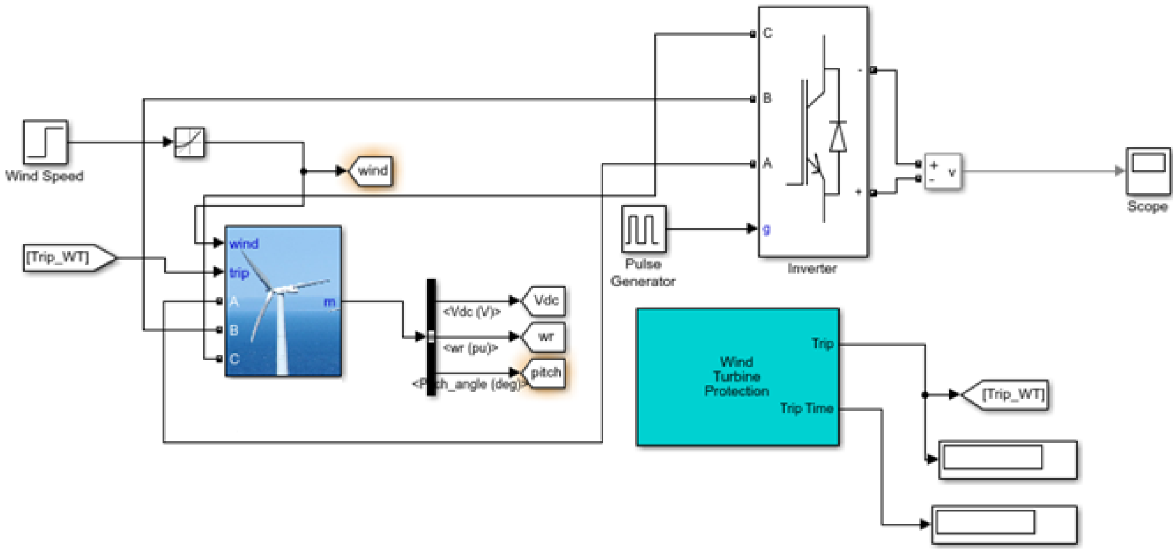

Fig. 4 Mathematical modeling of PMSM

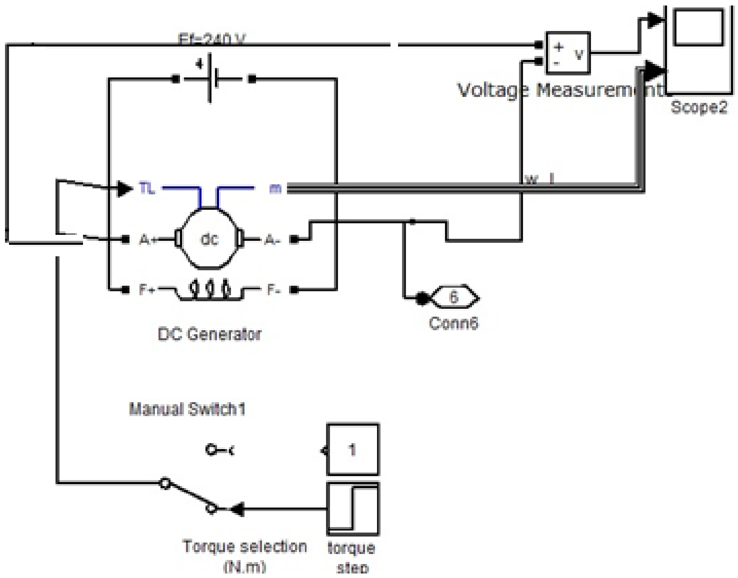

Fig 5 DC Generator Model

Modeling of DG

DG set converts fuel energy (diesel or bio-diesel) into mechanical energy by means of an internal combustion engine, and then into electric energy by means of an electric machine working as generator. For achieving constant DC output, DC generator is used in diesel system. The generator we are adopting in our system is DC generator. Fig 5 shows the modeling of DG.

1.4 MW Hybrid SAPS System

The proposed system for rural electrification is presented in this section. The mathematical modeling of PV module/wind/ diesel (DC generator) hybrid SAPS system is done in MATLAB/Simulink as shown in Fig 6. The output of all the sources of power generation is discussed in the modeling section. Now the hybridization is done by considering the output of PV, wind and diesel generator to be same i.e. 24 V DC. The output voltage of hybrid system can be fed directly for the off grid applications.

IV. Results and Discussion

Fig. 7 shows the output voltage of SAPS system used as input to the inverter. The voltage is found constant at 0.2 sec. Table II shows the output of Hybrid SAPS system.

V. Conclusion

The total power output of hybrid SAPS system is 1.4 MW at full load; this system will be adopted for off-grid applications i.e. directly feeding to the load. The output of the system is acting as input for inverter or it may be used for battery charging also based on the system we are adopting for off grid applications. But here we are replacing battery due to cost and life, as the output is continuous due to use of diesel generator in hybrid with solar and wind sources. The output is directly fed to the inverter and then can be used for meeting load demands.

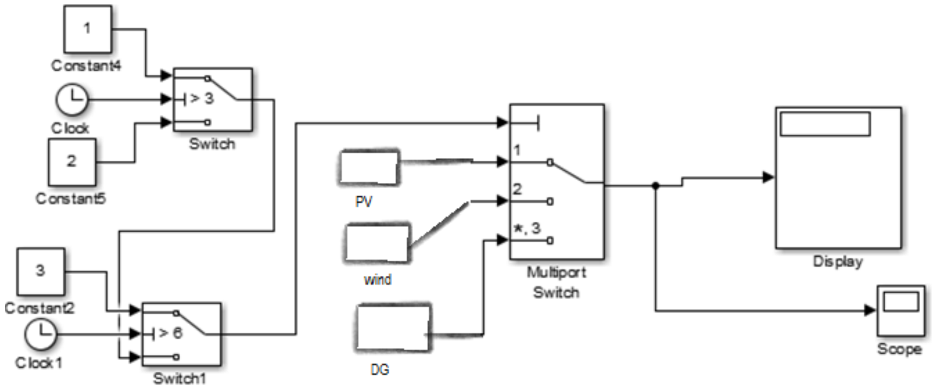

Fig. 6 Simulation model of Hybrid Controller SAPS system

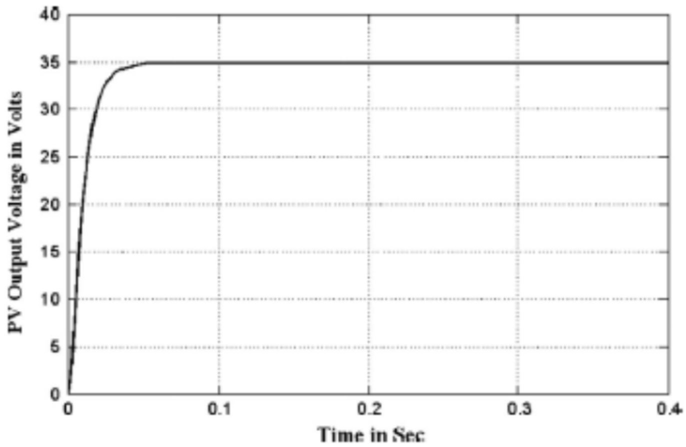

Fig. 7 Output from Hybrid Controller of SAPS system Injected to Inverter

TABLE II
OUTPUT OF HYBRID SAPS SYSTEM

S.No.	Terms	Ratings
1.	Total SAPS power output	1.4MW
2.	Output Voltage Solar Module	24 V DC
3.	Output Voltage Wind Turbine Generator	230 V AC
4.	Output Voltage DG	24 V DC
5.	Load Current	100 A
6.	Transformer (for wind output)	1:10 Stepped Down
7.	Converter	3 Phase (IGBT), 24 V DC

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