Analysis of PV Buck-Boost Converter Supplied Dc Motors

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Abstract: **The transient and steady state performance of separately excited dc motor coupled to centrifugal and volumetric pump loads supplied from Photovoltaic source through intermediate buck-boost converter is analyzed. The effect of duty ratio selection based on maximum power operation of PV source and maximum daily gross mechanical power is investigated on the Solar Cell Array operating point, motor armature voltage, armature current and motor efficiency variation. Studies are carried out by formulating mathematical models for the Photovoltaic source, d.c.motors, power converter and load. Simulation software was developed for the transient and steady-state analysis of PV supplied separately excited dc motors for different duty ratios of power converter and solar insolations. The performance of the motor driving the above two-load torque's is evaluated and compared when it is operating at maximum power operation and Gross mechanical operation.**

1. INTRODUCTION

The rapid trend of industrialization of nations, increased interest in environmental issues led recently to explore the use of renewable forms such as solar energy. Photovoltaic (PV) generation is gaining increased importance as renewable source due to its advantages like absence fuel cost, no noise and wear due to absence of moving parts and little maintenance etc., In particular PV systems are rapidly expanding and have increasing roles in electric power technologies, providing more secure power sources to the pumping systems, where it is not economically viable to connect the existing grid supply.

In Reference [1] the optimum operation of a combined system of Solar Cell Array (SCA) and a DC Shunt motor is achieved by means of a switching procedure of the SCA modules and direct current transformers as well as controlling the motor fluxes maximum mechanical energy output. Appelbaum [2] have analyzed the performance of dc motors (separately, series and shunt) supplied from PV sources. These studies reveals that the dc shunt motor powered by solar cells has inferior performance and a separately excited dc motor driving a centrifugal pump is the best candidate as for as better matching of the PV generator. Saied [3] formulated guidelines to construct the motor v-i characteristics for maximum daily mechanical power and to determine the optimal motor parameters to match the solar generator.

The electrical energy output from the PV array depends on the solar insolation and the available electrical energy intern depends on the conversion characteristics of Photovoltaic cells. From the knowledge of Power-vs-Voltage characteristic for each insolation there will be a particular (voltage, current) point at which the power output from the solar cell is maximum. To extract maximum power from the PV source a time-variable transformer (TVT) or a power converter is connected in between the PV array motor to derive maximum power from the PV source [5]. In [6] steady-state performance of d.c. Motors supplied from PV generators with step-up converter was investigated. It is established in the same study that there is unique duty ratio, which optimizes utilization efficiency of dc shunt motor supplied from PV array with intermediate converter driving a centrifugal water pump. Further, the study reveals that the drive speed and torque are less dependent on insolation levels.

The present paper brigout the transient and steady state performance separately excited dc motor driving centrifugal and volumetric pump loads fed from PV supplies with intermediate buck-boost converter. The converter duty ratio is selected for two different cases. (a) To extract the maximum power (MP) from the PV source, (b) to yield gross mechanical energy (GME) output. For these two cases the performance of the separately excited dc motor is evaluated and compared.

II. MATHEMATICAL MODEL OF THE SYSTEM

A. Mathematical Model of the System for Steady-State Analysis

The drive system mainly consists of Solar Cell Array, dc-dc converter and DC motor coupled to pump load. The dc - dc converter is a buck-boost converter with a variable duty ratio, which regulates the motor voltage and current to yield maximum power from SCA or maximum gross mechanical energy output. The motor is separately excited dc motor coupled to centrifugal pump or volumetric pump load. Mathematical models are developed in the following sections for individual components and combined together for the performance studies.

B. PV Generator Model

The PV generator is formed by the combination of many PV cells connected in series and parallel fashion to provide desired values of output voltage and current. This PV generator exhibit non-linear insolation dependent v-i characteristic. The PV generator considered [2] in these studies consisting of 18 parallel paths; each path contains 324 cells in series. The v-i characteristic of the PV generator is

$$V_g = -0.9 i_g + 23.697 A_1 \quad (1)$$

$$A_1 = \ln\{1 + (123.456(13.45 K_i - i_g))\}$$

Where "K_i" is percentage of insolation

C. Power Converter Model

The intermediate power converter is a buck-boost converter with a variable duty ratio. This converter regulates the motor voltage, current and continuously matches the output characteristics of the PV generator to the input characteristic of the motor so that maximum power is extracted from the SCA or the gross mechanical energy per day of the system is maximum. The dc-dc converter is assumed to be ideal, the output voltage and current of the converter for a chopping ratio of 'Y' is related to the solar cell voltage "V_g"

$$V_{av} = V_g Y \quad (2)$$

$$I_{av} = \left(\frac{I_g}{Y}\right) \quad (3)$$

$$\delta = \left(\frac{t_{on}}{T}\right) \quad (4)$$

$$Y = \frac{(\delta)}{(1.0 - \delta)} \quad (5)$$

D. Model of The dc Motor

When the separately excited d.c. Motor is supplied from PV supply through intermediate power modulator, the motor voltage and torque equations under steady-state are

$$V_{av} = E_b + R_a I_g \quad (6)$$

$$T_e = C_e I_g \quad (7)$$

$$E_b = C_e \omega_m \quad (8)$$

E. Model of the Centrifugal Pump-Load

Pumps may be volumetric or centrifugal types having different head - vs - flow characteristics. These pump-loads will develop speed dependent torque's. The speed - torque characteristics of centrifugal & volumetric pump loads including friction torque are given by

$$T_{L1} = A_1 + B_1\omega + C_1\omega^{1.8} \text{ Nm} \quad (9)$$

$$T_{L2} = A_1 + B_1\omega \quad \text{Nm} \quad (10)$$

III. Mathematical Model of the System For Transient Analysis

The transient performance of separately excited dc motor with PV supplies is different from when it is supplied with conventional d.c supplies. By using intermediate power converter the PV array can be operated at its maximum power point. Under such conditions knowledge of the transient behavior essential for satisfactory design and operation. These transient studies involves modeling of the various components of the combined system. When the separately excited d.c. Motor is supplied through PV supply with intermediate power modulator, the motor voltage, torque, back emf and load torque balance equations for the transient characteristics are

$$V_a = L_a\left(\frac{di_g}{dt}\right) + R_a i_g + C_e \omega_m \quad (11)$$

$$T_e = C_e I_g \quad (12)$$

The load torque balance equation is

$$T_e = J\left(\frac{d\varpi_m}{dt}\right) + B\omega_m + A + T_L \quad (13)$$

Where $T_L = T_{L1}$ for Centrifugal Pump and

$T_L = T_{L2}$ for Volumetric Pump

Rearranging the above equations then the resulting simulation model equations for separately excited dc motor are

$$\frac{di_g}{dt} = \frac{(V_a - C_e\omega_m - R_a i_g)}{L_a} \quad (14)$$

$$\frac{d\omega_m}{dt} = \frac{(C_e i_g - A - B\omega_m - T_L)}{J} \quad (15)$$

IV. PERFORMANCE ANALYSIS

A. Maximum Power Operation of SCA

For maximum utilization of SCA, a power converter is introduced in between SCA and motor. The duty ratio of the converter is changed accordingly to match the load to SCA. Adopting the procedure given [5] assuming power converter is ideal, all of the array power is delivered to the motor load. When SCA operating at maximum power point, the power absorbed by the load is equal to the power delivered by the SCA i.e.

$$P_m = V_a I_a = V_m I_m \quad (16)$$

Where V_m, I_m are SCA voltage, current respectively at maximum power point; V_a, I_a are the motor armature voltage, current respectively at maximum power point of SCA. The motor armature voltage and currents are expressed in terms of SCA voltage and current at maximum power point as

$$V_a = \delta_m V_m \tag{17}$$

$$I_a = \left(\frac{I_m}{\delta}\right) \tag{18}$$

Transforming the motor equivalent circuit to SCA side then the motor armature voltage equation becomes

$$V_m = \left(\frac{E_b}{\delta_m}\right) + I_m\left(\frac{R_a}{\delta_m^2}\right) \tag{19}$$

Rearranging the above equation

$$\delta_m^2 V_m - \delta_m E_b - I_m R_a = 0$$

Solution for duty ratio is

$$\delta_m = \left(\frac{E_b}{2V_m}\right) + \sqrt{\left(\frac{E_b}{2V_m}\right)^2 + \left(\frac{I_m R_a}{V_m}\right)} \tag{20}$$

For given SCA Maximum Power the motor armature current is obtained from the following equations

$$P_m = E_b I_a + I_a^2 R_a \tag{21}$$

$$E_b I_a + I_a^2 R_a - P_m = 0$$

$$I_a = -\left(\frac{E_b}{2R_a}\right) + \sqrt{\left(\frac{E_b}{2R_a}\right)^2 + \left(\frac{P_m}{R_a}\right)} \tag{22}$$

Where E_b given by eq's (8). The duty ratio of the converter is depends on the motor back emf which inturn depends on motor load. When the dc motor coupled to the load, for a given SCA maximum power (P_m, V_m, I_m) the back emf is obtained by solving eq's 9,12, and 22 for centrifugal pump load; eq's 10, 12 and 22 for volumetric pump load. Once back emf is calculated corresponding to P_m, the duty ratio of the converter, motor voltage, current and efficiencies are obtained.

B. Maximum Daily Gross Mechanical Energy

For given value of flux coefficient/mutual inductance of the machine it is not possible to make the SCA and motor to operate at maximum power points (P_m, V_m, I_m) at all solar insolations [3]. This is because of the motor v-i characteristics dependent on motor flux coefficient and copper losses in the machine. In such cases the system is made to operate at a point (P_m^*, V_m^*, I_m^*) of maximum mechanical energy output per day for a given daily insolation curve. This operating point can be found by knowing the SCA voltage, current corresponding to maximum power operation (V_m, I_m) using the following equations [3].

$$V_m^* = \frac{V_m\left(2R_a + 89.8\, I_m^{0.127}\right)}{\left(R_a + 89.8\, I_m^{0.127}\right)} \tag{23}$$

$$I_m^* = \frac{\left(89.8\, I_m^{0.873}\right)}{\left(R_a + 89.8\, I_m^{0.127}\right)} \tag{24}$$

$$P_m^* = V_m^* I_m^* \tag{25}$$

At this operating point $V_m^* > V_m$, $I_m^* < I_m$. For the machine under consideration the optimal flux coefficient [3] C_e=0.6626 makes the combined system operate at the maximum gross mechanical energy output. With these optimal parameters, P_m^*, V_m^*, I_m^*, back emf and duty ratio's are calculated using eq's (9,12,22)/ (10,12 and 22) at different solar insolations.

V. RESULTS AND DISCUSSION

A 120V, 9.2A, 1500rpm separately excited dc motor [2] was considered for simulation studies. The parameters of the machines are given in Table- 1. Based on the mathematical models developed in the preceding sections the converter chopping ratios are calculated for different solar insolations (a) maximum power operation of SCA and (b) maximum daily gross mechanical energy output. Fig.1 to Fig.4 represents the steady-state simulation results obtained for the above two cases. At lower solar insolations (<60%) the chopping ratio of the converter is smaller for volumetric pump load than when the motor driving the centrifugal pump load as shown in Fig.1.

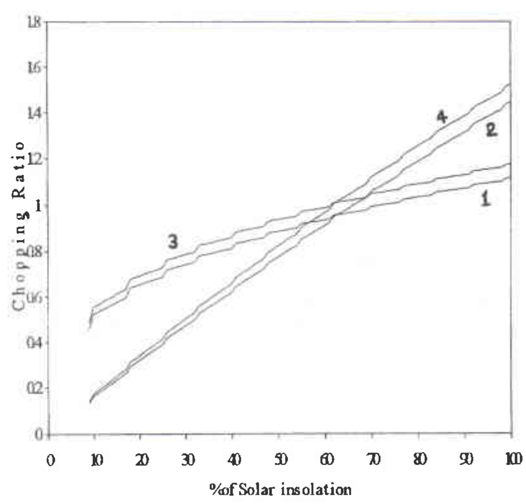

Fig.1. Chopping Ratio of the Converter

As a result, at lower solar insolations the dc motor draws higher current when it is driving the volumetric pump load resulting in increased thermal loading on the machine and reduced efficiency (Fig.3 & 4).

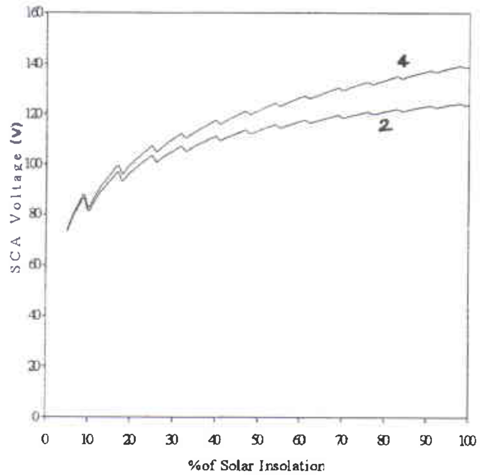

Fig.2. SCA Voltage Variation

This efficiency reduction is more at lower solar insolations when the motor is driving the volumetric pump load. From the simulation studies it is found that the separately excited dc motor operating at gross mechanical power outputs results in better performance with centrifugal pump loads than the volumetric pump loads.

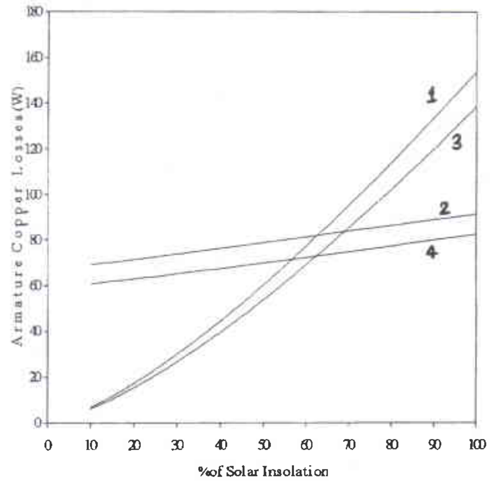

Fig.3. Armature Copper Losses

Using the eq(11) to eq(15) the transient performance characteristics of 120V, 9.2 A dc motor are generated. Fig.5 and Fig.6 represents the simulation results obtained for a solar insolation of 50% (0.5 p.u) and the duty ratio's are corresponding to maximum power operation of SCA, gross mechanical energy output. Transient response is better when SCA operates at gross mechanical output as compared to maximum power operation for both types of loads. Further, in either operating condition the transient response is poor with volumetric pump load, taking more time for acceleration of the drive, increased thermal loading on the machine during starting period. Gross mechanical operation slightly improves the transient performance of the motor for volumetric pump loads than maximum power operation.

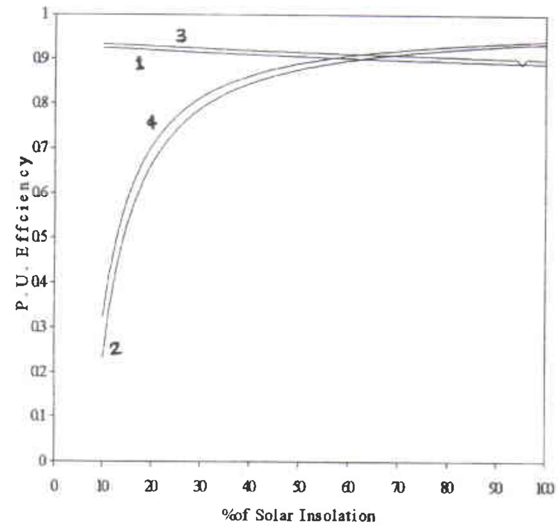

Fig.4. Motor Efficiency

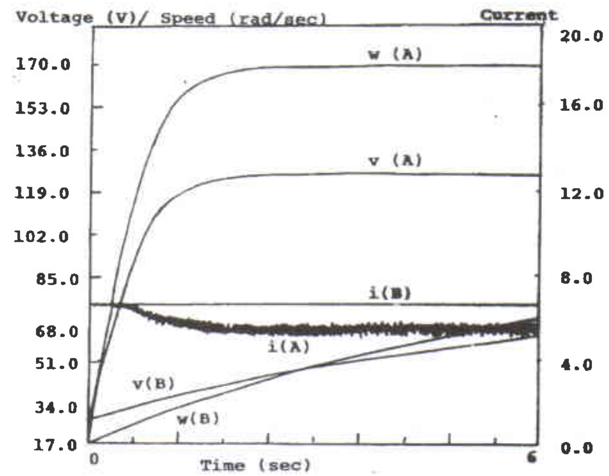

Fig.5.Transient Characteristics with Centrifugal Pump

A→ GME with Centrifugal Pump
B→ GME with Volumetric Pump
C→ MP with Centrifugal Pump
D→ MP with Volumetric Pump
w→ Speed
v→ Armature Voltage
i→ Armature Current
1→ Centrifugal Pump with MP operation
2→ Volumetric Pump with MP operation
3→ Centrifugal Pump with GME operation
4→ Volumetric Pump with GME operation

From the simulation results it is found that the dc separately excited motor driving centrifugal pump loads operating at gross mechanical energy output gives optimum performance compared other possible operations.

VI. CONCLUSIONS

The steady state and transient characteristics of dc separately excited motor with intermediate buck-boost converter are obtained. From the simulation studies it is observed that the use of converter will have the influence both on the transient and steady state behavior. Simulation studies show that the separately excited dc motor operating at gross mechanical energy output with centrifugal pump load will give optimum steady state and transient response. The simulation model developed can also be used for determination of performance with different types of intermediate power converters such as buck and cuk converters.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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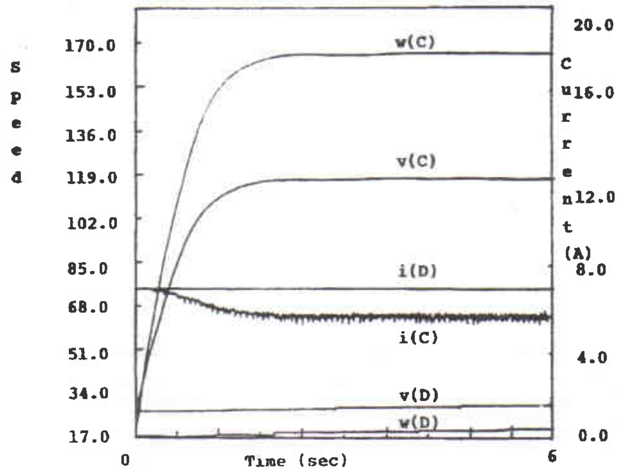

Fig.6 Transient Characteristics for Valuemetric pump

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List of symbols

V_g Solar Generator Voltage
V_a Converter Output Voltage
i_g Solar Cell Current
E_b Back EMF
R Armature circuit Resistance
L_a Armature circuit inductance
C_e Flux Coefficient
ω_m Shaft speed
T_l load Torque
T_e Electromagnetic Torque developed
J Moment of Inertia
δ Duty Ratio
δ_m Duty Ratio at maximum power operation

Table-1: Machine Data

V	120V
I	9.2A
N	1500rpm
R_a	1.50 Ω
L_a	0.02 H
C_e	0.621/0.6626
A_1	4.2
B_1	0.002387
C_1	0.00039