Novel Control Strategies For Photovoltaic Powered PMDC Motor Drives

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***Abstract*--This paper presents a novel PID dual loop controller for a solar photovoltaic (PV) powered industrial type permanent magnet DC (PMDC) motor drive, which is modeled to include existing nonlinearities in motor plus load inertia (J) and viscous friction (B). The proposed dual loop includes a speed control as the dominant control loop and a supplementary motor current limiting loop as an auxiliary regulating loop to limit excessive high current and sudden current excursions. Alternative control approaches are used to ensure energy efficiency, stability and system reliability while maintaining operation flexibility. A type B DC-DC chopper is employed to control the power transferred from photovoltaic PV array to the PMDC motor. The performance of different dynamic controllers are simulated and validated in Matlab/Simulink GUI environment. All simulation models of PV array, DC-DC chopper, PMDC motor, interface filters, and the controllers are modelled using Matlab/Simulink/Sim-Power model block library**.

***Key words*: - photovoltaic energy, PMDC motor, error driven controller.**

I. Introduction

THE growing demand for electrical energy throughout the world has motivated the use of new renewable sources of energy. Among the unconventional renewable energy sources that have been studied, PV energy is now becoming a promising economical renewable/alternate energy source. Except its higher initial installation costs, the PV energy has many advantages: it is reliable and requires little maintenance. It costs little to operate and almost has no environmental impact. It's both modular and flexible in terms of economical sizes and range of applications. It is also most suited to arid and developing countries.

The stand-alone photovoltaic (PV) utilization system displays an inherently nonlinear current-voltage relationship, requiring a dynamic online search and identification of the optimal maximum power point (MPP). The performance of any PV system depends also on the electric load operating conditions. When designing the PV system, the combined effect of the electric load, ambient temperature and solar irradiation variations should be considered all [1-3].

Photovoltaic PVA-solar powered electrical systems comprise different components and subsystems to be controlled separately. Since the generated solar PV power is a function of Solar Irradiation, Ambient Temperature as well as other uncontrollable environmental conditions, it requires extra caution to design controllers that handle unpredictable events and maintain efficient load matching power. In this study, a PV solar array model developed for Matlab/Simulink/SimPower GUI environment [4, 5] is used. The controller's performances are increased using dynamic error in order to handle PV array-load bus power matching as well as specific load controlling purposes such as keeping the DC load bus voltage at constant value, operating the PMDC motor at a specific speed, and moving a robot arm, a door, or a radar at a certain position. The novel dynamic error driven controllers has flexible design criteria's so that they can easily be modified and extended for controlling different systems [6]. Different kinds of controllers have been used in three different parts of the solar PV powered PMDC motor drive scheme studied here. One of these parts is the speed control of the PMDC motor load, one of the other parts is the DC load bus voltage control, and the third part is optimum power matching control between the PV array and the load bus.

One of the key challenging issues of PV array schemes is the power matching problem between the PV array and the load. Since the power generated by PV array is unpredictable due to changing solar irradiation level and ambient temperature, it is an important task to maintain a constant load voltage and power. Besides, the load being powered from the PV array may have excursions and switch on/off cases that affect the power matching. Since the output voltage of a PV array also depends on the current drawn from the array, load switching and excursions affect the array output voltage. Therefore the control problems in a PV array system are multi-dimensional and require dynamic error driven approaches to extend the single input single output (SISO) controllers for handling systems that require multi input multi output (MIMO) controllers [7].

The PMDC motor is used to drive a variable torque load, an elevator type load or a production line system. Each one of these load types requires different control strategies and different controller parameters. Therefore the controllers used in such a system must handle all the cases with an adaptive property in nature. The addition of dynamic error driven loops to the controller structures increases the ability of the controllers to handle the changes occurring in the overall system [8].

II. General System Description

Fig. 1 shows the proposed stand-alone photovoltaic scheme. This system comprises two load paths at different voltage levels. Each load path has one DC-DC chopper to obtain two different DC load bus voltages one for the loads to be operated below 200 V DC and the other one is for the loads to be operated at 600 V DC. The choppers for DC voltage control at the load busses are controlled using classical PI controllers. The 50 V load bus feeds a series R-L load. The 600 V load bus is used to supply power to PMDC motor, which is considered to be operated to drive loads having different torque-speed characteristics. The PMDC motor drive part of the scheme is mainly studied in this paper. All the motorized loads are considered to be operated at different load torque levels under changing ambient temperature and solar irradiation levels to the PV generator.

The proposed cottage PV energy system has the following parts:

1. PV array string of series/parallel modules. PV array is connected with charger regulator which is an interfacing device between the PV array, backup batteries, and the DC load bus. The backup Battery unit is charged if there is more sun power available and used when the power from the PV panel is low. The charge regulator is used to manage the power transfer process from PV array to DC loads and to the battery unit. The PV array modelling has been discussed in [4] and will not be repeated here.
2. Power conditioner circuits.

a) Blocking Diode: To block the reverse current flow.

b) DC side filter (R_f, L_f): The DC side filter allows for a valid quasi static model of the PV array and ensures sufficient time scale decoupling of the three supplementary control loop.

c) Type A MOSFET or IGBT DC/DC converter (chopper) using Pulse Width Modulated (PWM) switching circuit.

3. Input side Capacitor (C_I): It's a large value capacitor works as storage media. Loads: Here the loads are hybrid type consists of both resistive and dc motors such as the permanent magnet DC motor used in the simulation.

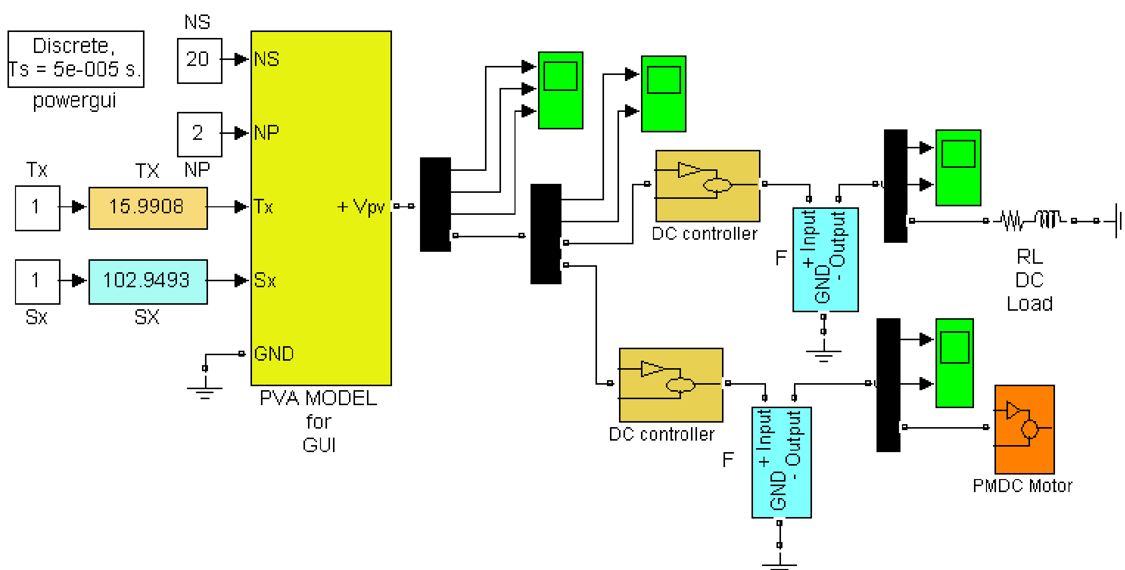

Fig 1. Standalone PV Photovoltaic–PMDC Motor Drive Utilization Scheme.

The proposed stand alone PV Array system generates a voltage of about 800 V at the output of the charge regulator. Then this voltage is reduced to 50 V and 600 V using two separate PI controlled DC-DC choppers as shown in Fig. 1. The chopper on the right upper part is controlled to obtain a 200 V DC bus for small DC loads. The second chopper on the right bottom is controlled to obtain a 600 V DC load bus for larger DC loads. The proposed PV powered large PMDC motor is connected to this 600 V DC bus, and controlled by using another DC-DC chopper as given in Fig. 2.

DC MOTOR

DC motors have lots of desirable properties. Some of them are reliability, durable, Low cost, and low operation voltages, having positive conversion coefficients between electrical and mechanical components, having size and design variation.

A permanent magnet dc motor (PMDC) is one of the DC motor types. PMDC system converts electrical power provided by a voltage source to mechanical power provided by a spinning rotor by means of magnetic coupling. The equivalent circuit of a PMDC motor is illustrated in Fig. 2. The parameters and symbols which were used in simulating the system are given in Appendix. The armature coil of the DC motor can be represented by an inductance (L_m) in series with resistance (R_m) and with a series induced voltage (e_m), which opposes the voltage source.

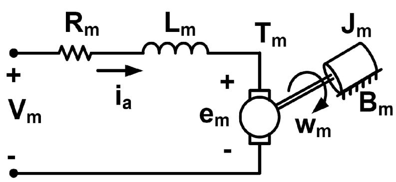

Fig. 2. The equivalent circuit of a DC motor.

A differential equation for the equivalent circuit can be derived by using Kirchhoff's voltage law around the electrical loop.

$$V_m(k) = R_m \mathrm{I}_a(k) + L_m \frac{d\,\mathrm{I}_a(k)}{dt} + e_m(k) \qquad (1)$$

Where:

1. $e_m(k) = K_E \omega_m(k)$
2. i_1 =constant; therefore $K_E = K_T$

The sum of torques of the motor must be equal zero, therefore,

$$T_e(k) - J\frac{d\omega_m(k)}{dt} - B\omega_m(k) - T_L(k) = 0 \qquad (2)$$

The electromagnetic torque is proportional to the current through the armature winding and can be written as

$$T_e = K_T i_a \qquad (3)$$

The load torque is given by

$$T_L = K_0 + K_1\omega_m + K_2\omega_m^2 \qquad (4)$$

Where, the coefficients K_0, K_1 and K_2 are chosen as given in the Appendix. The differential equations in state space form for the armature current and angular velocity can be written as

$$\frac{d}{dt}\begin{bmatrix} i_a \\ \omega_m \end{bmatrix} = \begin{bmatrix} -\frac{R_m}{L_m} & -\frac{K_t}{L_m} \\ \frac{K_t}{J} & -\frac{B}{J} \end{bmatrix}\begin{bmatrix} i_a \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{1}{L_m} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix}\begin{bmatrix} V_m \\ T_l \end{bmatrix} \qquad (5)$$

Where i_a and ω_m are motor armature current and speed. The second order model of the PMDC motor is modelled in Matlab/Simulink by modifying the parameters of the blocks shown in Fig. 3.

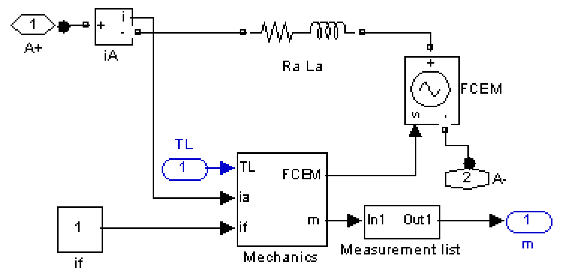

Fig. 3. The Simulink model of the PMDC motor.

The values of the parameters used in PMDC motor modelling are given in the Appendix. Load torque is taken as generalized nonlinear term:

$$T_L(\omega_m) = 200 + 1.2\omega_m + 0.01\omega_m^2 \qquad (6)$$

The nonlinear inertia J and viscous friction B in Fig. 3 have the following forms:

$$J(\omega_m) = J_0 + J_1\left|\omega_{mpu}\right|^2 \qquad (7)$$

$$B(\omega_m) = B_0 + B_1\left|\omega_{mpu}\right|^2 \qquad (8)$$

The values of the parameters in (7) and (8) are given in the Appendix. The operational block diagram of the chopper controlled PMDC motor scheme is shown in Fig. 4. It should be noted that the connection port marked as 1 is connected to the 600 V bus of the PV generation unit.

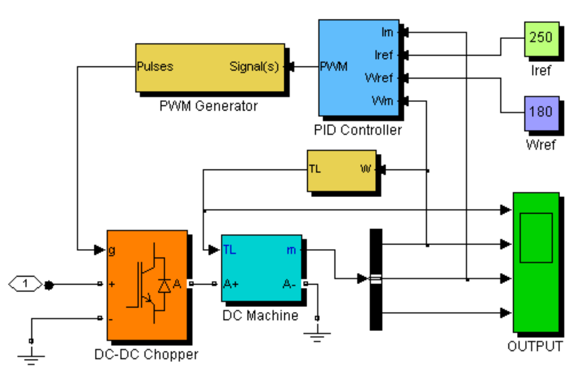

Fig. 4. Simulink Model of the large PMDC motor utilization Scheme.

III. PID Dual Loop Controller

PID stands for Proportional, Integral, and Derivative controllers, which are designed to eliminate the need for continuous operator attention and used automatically adjust some variables to hold the process variable at the reference value.

In this study, two different types of control strategy have been applied. In Type-I, there are motor speed and motor current loops as shown in Fig. 5.

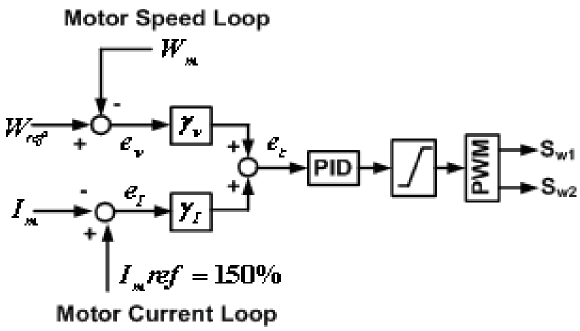

Fig. 5. PID Speed & Current dual loop controller (Type-I).

In Type-II, only the speed loop is used. Type-II control scheme is shown in Fig. 6.

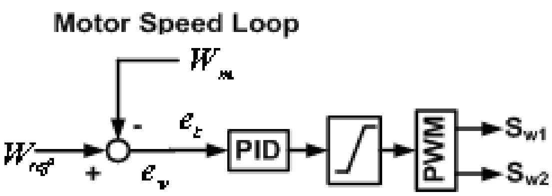

Fig. 6. PID based speed regulation controller (Type-II).

Dual loop PID control system comprises two loops. There are motor speed loop and motor current loop. The global error signal (e_t) is the sum of these two basic loop errors, namely the motor speed, motor current errors. The weighted sum of these two errors is the total error input to the controller, which is either classical PID controller or a fuzzy logic controller (FLC). The weighting coefficients for speed and current errors are represented by γ_w and γ_I, respectively to yield the total weighted error as;

$$e_t = \gamma_w \cdot e_w + \gamma_p \cdot e_p \tag{9}$$

The loop weighting factors (γ_w and γ_I) are assigned for satisfactory fast and stable dynamic operation.

The current loop has auxiliary properties as an additional loop since the motor speed is the one actually controlled in the system. The reason of using a current loop is the prevention of high current ripples and spikes, which may cause damages in the motor. Therefore, the current loop performs like a limiter more than a controller. Here PID controller or another controller controls the sum of the loop errors. So, the controller continues to generate a non-zero output until each one of the two loop errors becomes zero.

The global error goes into PID controller block. After the signal is processed in the block, the PID controller output is limited by the limiter. The limited signal goes into PWM block and the block generates two pulses by comparing a triangular carrier waveform to a reference modulating signal. Two pulses are fed to the two-quadrant DC-DC chopper. The PMDC motor armature voltage is controlled by adjusting the switching functions for the chopper switches. Switch SW1 for the main speed regulation loop, while switch SW2 is used for the optional supplementary current limiting/braking loop [9].

IV. Simulation Results

In order to include the effects of DC-DC chopper switching, the PMDC motor model used in the simulation should be a switched mode model. Therefore, as the chopped DC voltage is applied to the motor, the energy stored in armature winding and rotating armature mass is included in the model. By using the Dual-loop PID Controller and Single-loop PID Controller, it is expected to have a smoother, overshoot free, fast and less sensitive speed controller when compared to those of classical ones [10].

The proposed general Switched Mode PV-PMDC Motor Drive Model with the Dual-Loop Error Driven speed controller are fully validated in this paper for effective speed trajectory tracking of the PMDC motor drive under different photovoltaic excursions, loading conditions and parameter variations; Such as being fed by a photovoltaic solar cells voltage source whose voltage may suddenly change ±50% due to solar irradiation and temperature changes while driving a complex mechanical load with a parameter sensitive and non-linear torque-speed characteristics. Since Renewable DC sources such as photovoltaic solar arrays can generate voltages that are generally unpredictable depending on the solar insulation or temperature levels, DC-DC choppers are used to control the motor armature voltage to match the load to the PV Solar Source. Therefore the proposed switch mode model for the PMDC motor can result in more reliable dynamic response and accurate speed tracking performance. The Dual-Loop Error Driven PID Controller and Single-Loop error Driven PID Controller are used to keep the motor armature voltage between specified operational limits and ensure excellent speed reference tracking under source, load excursions and parametric variations. Both Controllers scheme inherently allows any dynamic excursions or parameter variations to be taken into account so that the controller regulator parameters are dynamically adapted by reducing the error changes in the motor parameters [11].

Both control structures are validated for effective reference speed tracking under normal conditions as well as parameter, photovoltaic source and/or load changes and sudden excursions.

The full PV conversion scheme was digitally simulated using MATLAB/SIMULIK software. The Solar cell equivalent circuit was created as a block called PV source as shown in Fig. 1, which simulates the nonlinear V-I characteristics of the solar panel based on the voltage-current relationship. The speed of the PMDC Motor on DC part is controlled trough an A type DC-DC chopper using the Dual-loop controller. Dual-loop dynamic error driven controller uses speed and current feedback to handle any excursion occurs due to load variations or due to solar irradiation and temperature variations on PV side.

The motor speed, current and torque of the PMDC motor are depicted in Fig. 7 and Fig.8. The tracking performance of the one-loop dynamic error driven controller is shown in Fig.7 and Fig. 8 for step changes in mechanical torque input. The simulation results confirm that the motor speed can be kept at desired levels when the load torque has a stepwise increase.

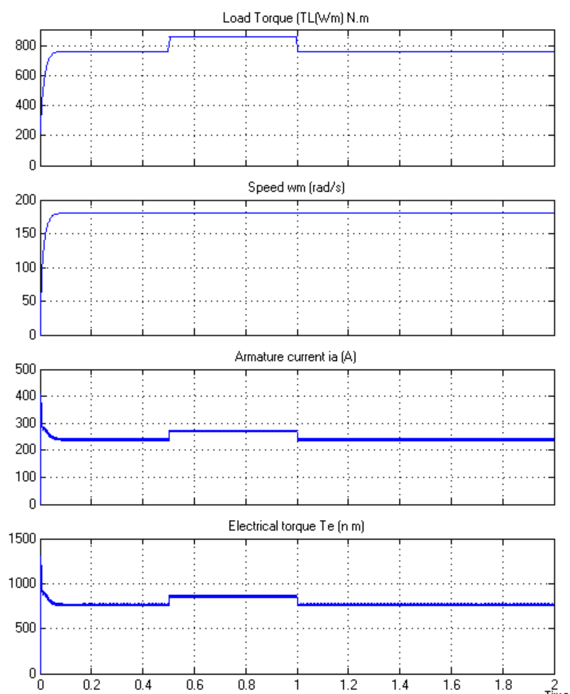

Fig. 7. Load torque, Speed, current and Electrical torque responses of the PMDC motor for step changes in torque using Dual-loop PID Controller.

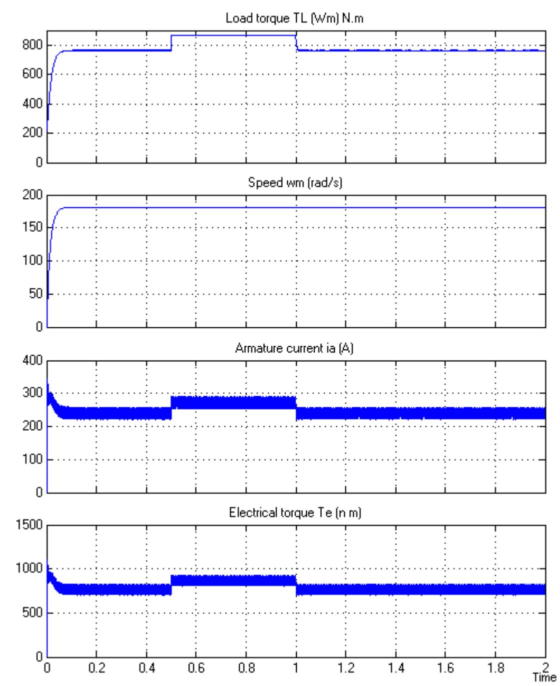

Fig. 8. Load torque, Speed, current and Electrical torque responses of the PMDC motor for step changes in torque using Single-loop PID Controller.

V. Conclusion

The paper presents a novel dynamic dual loop speed and current controller for a standalone PV powered PMDC motor drive. Digital simulation results validated the two key requirements of Speed reference tracking. This proposed standalone low cost dual loop PV powered PMDC Scheme has an online dual speed and current tracking controller that varies the pulse width modulation sequence to the Type-A DC-DC (chopper) to provide a a robust dynamic speed reference tracking while limiting inrush current conditions that can damage the permanent magnet in addition to ensuring near dynamic matching-condition between the PV array input and the equivalent hybrid motor plus load equivalent resistive load. The dynamic dual loop controller continuously searches for best PV-Utilization level while following required Reference speed. The same dynamic dual loop controller is now being extended to other new applications including Guided-Vehicle, PMDC-Wheel-Driven Electric Car and other mechanical refrigration, chiller, ventilation and water pumping type loads. PV standalone schemes are now very attractive for small scale applications in Cottage and Village Electricity as well as combined Irrigation and Water Pumping. PV-Systems can be used in ventilation and air-conditioning as an excellent measure for electric grid system capacity release and demand side management.

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APPENDIX

Table A1. Parameters used in the paper.

Voltage source	V_m	600V
Inductance	L_m	5mH
Resistance	R_m	0.05 Ω
Induced voltage	e_m	
Actual rated speed	$w_{a\text{-rated}}$	188.5 rad/s
Back emf constant	K_e	3.183 V.s/rad
Rotor moment of inertia	J_0	0.05 kg.m^2
Rotor moment of inertia	J_1	0.05 kg.m^2
Viscous friction coefficient	B_0	0.005 N.m.s/rad
Viscous friction coefficient	B_0	0.01 N.m.s/rad
Electromagnetic torque	T_e	Nm
Load torque	T_L	Nm
Motor speed weighting factor	γ_w	10
Motor current weighting factor	γ_I	0.1
Proportional constant	K_p	150
Integral constant	K_i	5
Derivative constant	K_d	2
Coefficient 0	K_0	200
Coefficient 1	K_1	1.2
Coefficient 2	K_2	0.01
Number of cells in series	NS	20
Number of cells in parallel	NP	2