SINGLE STAGE AUTONOMOUS SOLAR WATER PUMPING SYSTEM USING PMSM DRIVE

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Abstract This paper presents a single stage standalone solar photovoltaic (SPV) array fed water pumping system using a permanent magnet synchronous motor (PMSM). The vital contribution of this work includes: (i) development of the novel modified vector control (MVC), which improves the torque response of the system, (ii) development of a novel single stage variable step size incremental conductance (VSS-INC) technique, which provides a fast maximum power point tracking (MPPT) and eliminates the need of intermediate stage DC-DC converter and (iii) introduction of SPV power feed-forward term (FFT), which accelerates the overall response of the system under dynamic conditions.

This system includes a SPV array, a three-phase voltage source inverter (VSI), a PMSM and a pump. The SPV array converts solar energy into electrical energy. The VSI acts as power processing unit (PPU), which supplies desired currents to drive the PMSM. As the PMSM rotates, the pump coupled to the motor accomplishes the objective of water pumping. This system is modelled and simulated using MATLAB/ Simulink with available simpower system toolbox and the behavior of the system under varying atmospheric conditions are validated experimentally on a developed prototype in the laboratory.

I. INTRODUCTION

Renewable energy (RE) generation and effective utilization of available energy resources, have emerged as an exemplary panacea for increasing carbon footprint, depleting fossil fuels, increasing global warming and changing climatic conditions [1]. Clean nature, noiseless operation and abundant availability even at remote locations, have made the solar energy best form of RE available in the present scenario [2]. Decreasing capital cost, minimal maintenance cost and zero operating cost, have made solar photovoltaic (SPV) system an excellent conceivable way to harness solar energy [3-4]. Recently, SPV fed water pumping is receiving wider attention [5].

For areas having no accessibility to the grid and good solar insolation availability for most of days in a year, the solar water pumping (SWP) is meeting the water requirement for daily basic activities [6]. Moreover, SWP is providing a great boost to agricultural and industrial activities [7-8]. SPV integrated water pumps experience some of the potential challenges such as reduced efficiency, increased DC link voltage instability, sluggish response and high capital cost [9]. Although several researches have been carried out to mitigate some of these challenges, however, still insufficient literature is available to cope up with all these issues.

This work is intended to meet most of the problems associated with SWP. Conventional drives used for SWP are quite inefficient. The evolution of permanent magnet motors, has led to reduction in losses up to a greater extent. Permanent magnet synchronous motor (PMSM) and brushless DC motor (BLDC) are the two mostly used variant of permanent magnet machines [10]. PMSM possess inherent advantages of high efficiency, low torque ripples, low noise, high air gap flux density, high power to weight ratio, high torque to inertia ratio, quick acceleration and deceleration capability, high power factor and compact design [11]. This makes the motor best suited for SWP.

Most of the existing topologies for SWP, use induction motor (IM) for driving the pump, however, a comparative field test analysis performed by Brinner et.al. [12] on electric submersible pump (ESP) reveals that the permanent magnet motors (PMM) based ESP offers 20 % reduced consumption compared to IM based ESP of similar rating. As the open loop control of PMSM, is not recommended, PMSM suffers the drawback of complex speed control. Vector or field oriented control and direct torque control (DTC) are generally used techniques for speed control of PMSM [13].

DTC is simpler as compared to vector control, however, it has an inherent issue of increased torque and flux ripples. This issue has been addressed in various existing literature, however, the solution comes either at the cost of increased computational burden or increased hardware components [14-15]. V/f is also one of the rarely used technique for speed control of PMSM as it has a drawback of sluggish response and requires stabilizing loops for high speed operation [16-17]. Vector control technique provides an excellent speed control [18].

Here performance wise, PMSM is converted to equivalent separately excited DC machine [19]. The DC machine has an advantage of decoupled orthogonal flux and torque components. The flux and torque are controlled, respectively by controlling field current (If) and armature current (Ia). This control is extended to PMSM by considering the motor in a synchronously rotating reference frame (d-q) so that the sinusoidal quantities look like DC in steady state condition. The orthogonal direct (d) axis and quadrature (q) axes currents are the components of stator current and can be controlled separately analogous to a DC machine.

The reference direct axis current is controlled in accordance with required flux, whereas the reference quadrature axis current is controlled in accordance with the required torque. A modified vector control (MVC) technique is used here, through utilizing an extra control loop i.e. torque control loop and a SPV power feed-forward term (FFT). The incorporation of torque control loop reduces the burden on the speed controller and improves the torque response whereas the introduction of SPV-FFT accelerates the overall response of the system.

For the extraction of optimum power from SPV array, maximum power point tracking (MPPT) techniques are used. Numerous MPPT techniques such as an incremental conductance (INC), perturb and observe (P&O), fuzzy logic control, neural network, fractional Voc, fractional Isc and many other are discussed in the existing literature. Podder et al. [20] have presented an in-depth analysis of different MPPT techniques. Among existingMPPT techniques, P&O and INC are the two widely used techniques for SWP [21-23]. The P&O exhibits a straight forward control approach involving perturbation of the SPV array voltage towards the maximum power point (MPP). However, this method suffers from the drawback of steady state oscillations due to perturbations [21].

These oscillations result in power loss and are ineffective for maximum power extraction. The principle involved in MPPT using an INC method, relies on the fact that the incremental conductance and instantaneous conductance of the SPV array are equal at MPP [22]. Theoretically, this method gives no steady state oscillations as once the MPP is reached, there is no need of any further perturbation until the change in conductance takes place. However, due to the practical limitation of resolution of step size, the oscillations are non-zero all the time [23].

Even though P&O technique is simple and easily implementable, an INC algorithm gives accurate and fast MPP tracking during transients. An INC method of MPPT usually has fixed step size nevertheless, Yang et al. [24] have proposed an INC algorithm that uses variable step size by altering the step size of the duty ratio with every iteration. However, as suggested algorithm can be used only for two stage MPPT, it is well known that a single stage topology eliminates the requirement of intermediate DC-DC converter and, therefore, better from the view point of efficiency, size and cost.

Keeping the benefits of single stage topology in view, this work uses a single stage variable step size incremental conductance (VSS-INC) MPPT algorithm. This system for SWP is designed, modelled and simulated under MATLAB/Simulink environment and the hardware validation is carried out on a developed prototype in the laboratory. This system uses a single stage VSS-INC MPPT algorithm for optimum power extraction from SPV array and MVC for speed control of PMSM.

II LITERAUTRE REVIEW

B. Singh, A. K. Mishra and R. Kumar, explains Solar energy is a clean energy and it is increasingly being used all over the world. In this study, a water pump drive has been designed with a switched reluctance motor (SRM) to be powered by a photovoltaic energy source (PV). A boost converter has been used to increase the voltage of the PV source. The mathematical model of the system has been composed in the Matlab/Simulink and simulation results have been obtained. Output voltage of the boost converter has been controlled by using a PID controller at 50 kHz switching frequency.

F. Niu, K. Li and Y. Wang, proposed A space-vector pulse-width modulated voltage-fed inverter direct-torque controlled permanent magnet synchronous motor (PMSM) drive is presented in this work. A d-q model of the permanent magnet synchronous motor was developed in the rotor reference frame. Then a control method based on optimal inverter voltage selection through space-vector pulse-width modulation was developed to produce the firing signals for the six switches of the three-phase voltage source inverter in order to select the optimal inverter output voltages to supply the motor. Since current depends on voltage and electromagnetic torque depends on current, control of inverter voltage amounts to control of torque.

P. Sharma, and V. Agarwal," proposes Under partially shaded conditions, the current through a photovoltaic (PV) string is limited to the current produced by its most shaded module, reducing the overall PV array output power. A current compensation-based distributed maximum power point tracking (DMPPT) scheme may typically be used to maximize power output under these conditions.

III SYSTEM CONFIGURATION AND OPERATION

The configuration for SWP system, is shown in Fig. 1. This system comprises of (from left to right) SPV array, a three-phase voltage source inverter (VSI), a PMSM and a water pump. A diode (D) is used between SPV array and VSI to stop the flow of any reverse current into SPV array. The SPV array consists of appropriate number of series and parallel combination of SPV modules. As the photons strike the surface of the SPV array, electrical energy is generated. This generated electrical energy is fed to the DC link of VSI. The VSI acts as power processing unit. It rotates the PMSM with pump coupled to it and thereby converts this electrical energy into rotational mechanical energy. This SWP system consists of only one energy storing element i.e. DC link capacitor (Cdc). Assuming the system to be lossless, during transient condition,

$$P_{pv} = P_{C_{dc}} + P_m \tag{1}$$

$$P_{C_{dc}} = V_{dc} C_{dc} \frac{dV_{dc}}{dt} \tag{2}$$

Where, Ppv, PCdc and Pm are PV array, DC link capacitor and motor output power, respectively.

$$P_{pv} = V_{dc} C_{dc} \frac{dV_{dc}}{dt} + \tau_m \omega_m \tag{3}$$

Where, τm and ωm are motor torque and speed, respectively. During steady state condition, Vdc remains constant.

Therefore,

$$\frac{dV_{dc}}{dt} = 0 \tag{4}$$

Hence, (3) becomes as,

$$P_{pv} = 0 + \tau_m \omega_m \tag{5}$$

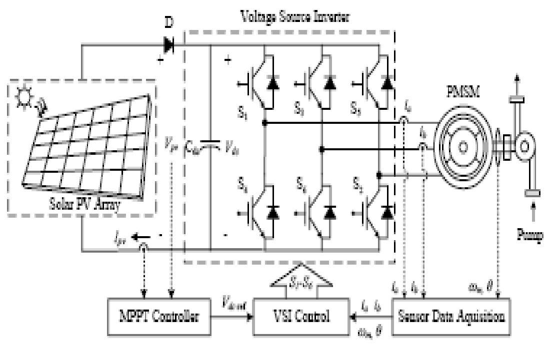
For a pump type load, the torque is considered as,

$$\tau_m \propto \omega_m^2 \tag{6}$$

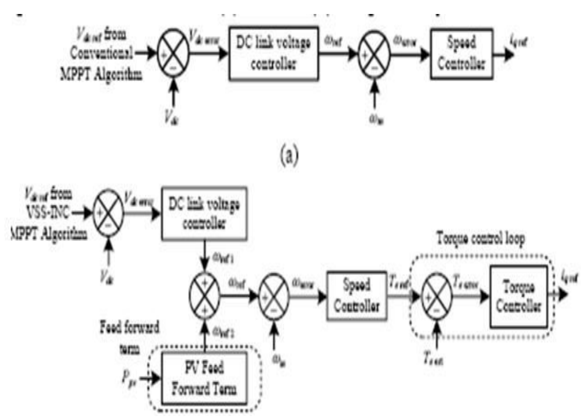
Therefore, (5) becomes,

$$\tau_m = K_m \omega_m^{\,2} \qquad (7)$$

$$b^{bn} = K^{m}\omega^{m}{}_{3}$$



Configuration diagram of SWP system



iq ref generation using (a) Conventional and (b) Modified vector control

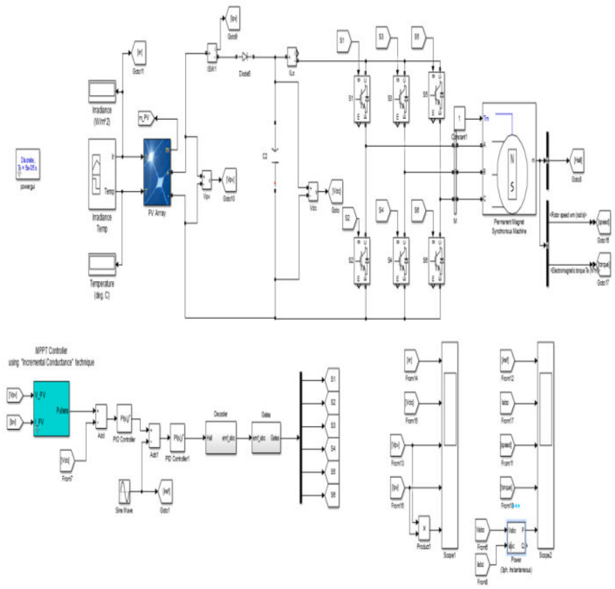
IV SIMULATION RESULTS

The performance of this system is investigated through simulation studies. The complete system is simulated using MATLAB/Simulink and its performance is studied during starting and steady state at different insolation levels. The system performance is also studied under dynamic condition. Dynamic response is analyzed through sudden change in insolation and temperature. The performance is analyzed by assessing the variation in SPV array parameters: insolation (S), SPV array voltage (Vpv), SPV array current (Ipv) and SPV array power (Ppv); PMSM parameters: motor current (iabc), motor speed (ωm), load torque (Tl) and load power (Pl); and reference parameters: reference DC link voltage (Vref) and reference motor current (iref).

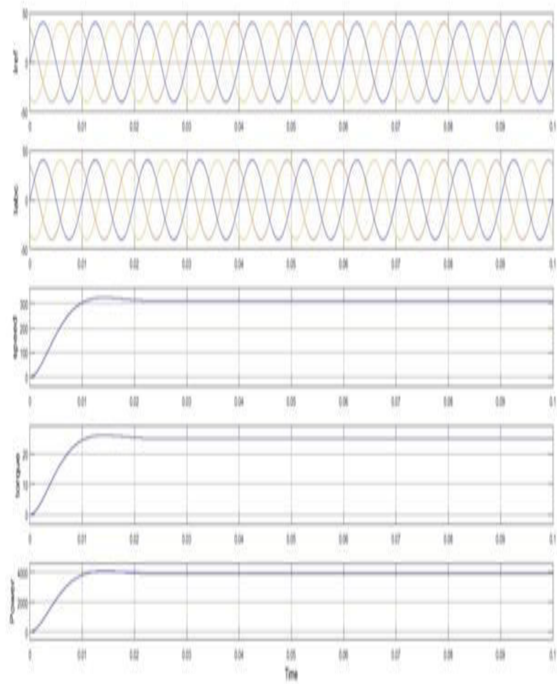
A. Starting and Steady State Performances

The starting and steady state performance of the system at a solar insolation of 1000 W/m2 and 500 W/m2, respectively at a constant temperature of 25 °C. are showing in below figures

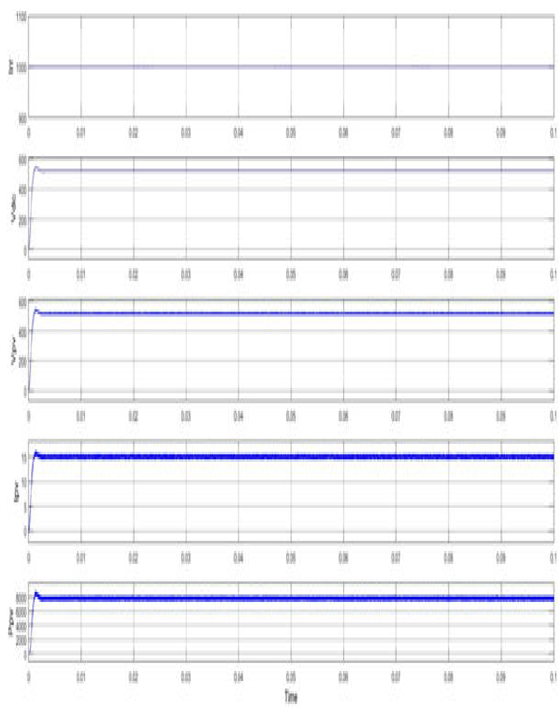
The motor is drawing twice the steady state current during starting. Since PMSM is an electromechanical device and has a larger time constant compared to electrical system, the motor parameters are taking more time to come to steady state compared to SPV array parameters. The motor is starting from zero speed and reaching the steady state speed within 0.04 s.



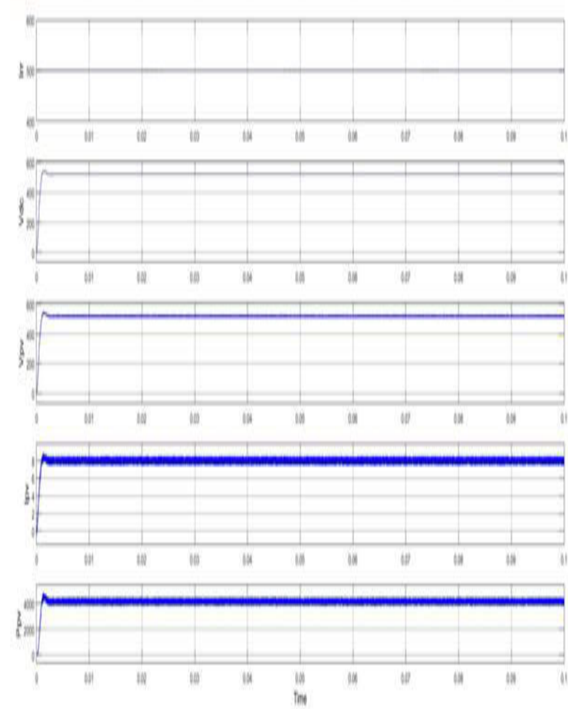
Simulink model



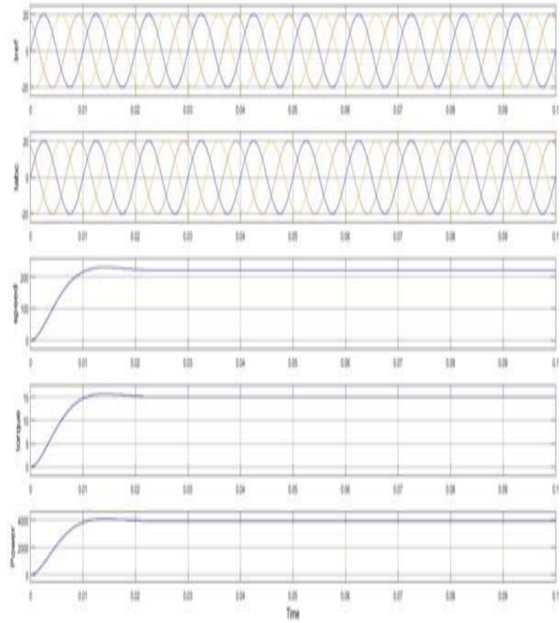
Power torque and speed



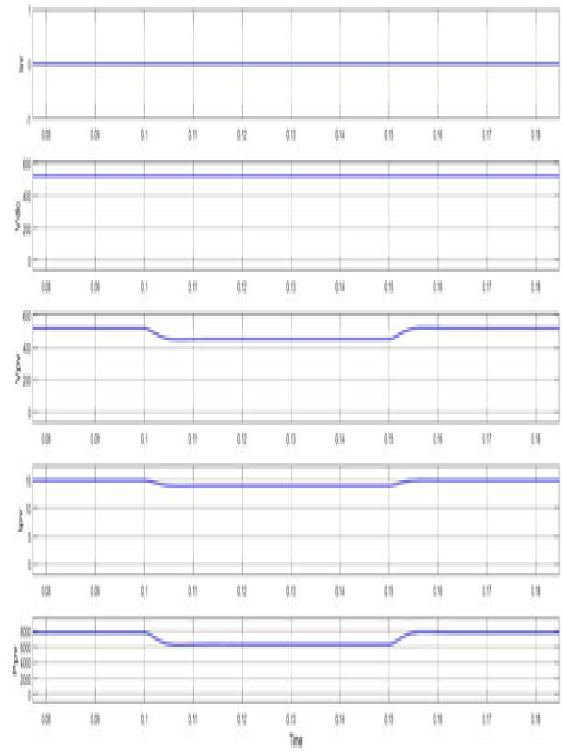
A Starting and steady state performance for (a-b) insolation of 1000 W/m2



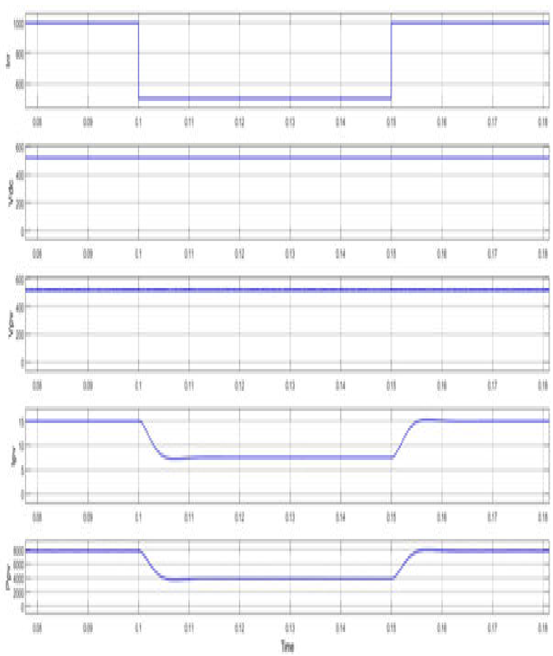
Insolation of 500 W/m2 PV current,power and voltage



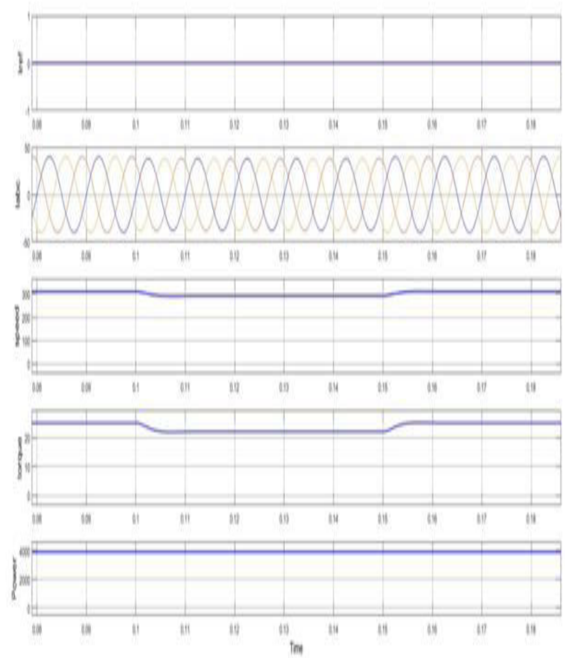
Starting and steady state performance for (a-b) insolation of 1000 W/m2 (c-d) insolation of 500 W/m2



Dynamic performance during temperature change (a) from 50 °C



From 1000 W/m2 to 500 W/m2



Dynamic performance during temperature change (a) from 25 °C

B. Dynamic Performance under Varying Insolation

Fig. 6 (a) and Fig. 6 (b) are showing the system dynamic performance during insolation change from 1000 W/m2 to 500 W/m2 and from 500 W/m2 to 1000 W/m2, respectively, at a constant temperature of 25 °C. Fig. 6 (a) is showing a change in insolation from 1000 W/m2 to 500 W/m2 at 0.1 s. The insolation change is marginally affecting the SPV array voltage (Vpv), however, greatly affecting the SPV array current (Ipv). Since the number of free electrons generated through the breaking of covalent bond due to striking of photons at the PN junction is proportional to solar insolation, the SPV current (Ipv) is reduced to almost half for change in insolation from 1000 W/m2 to 500 W/m2. This is reducing the SPV power to almost half the rated value. The motor parameters are also varying accordingly. The reduction in insolation is reducing the motor speed (ωm) and load torque (Tl) and eventually the load power (Pl). The system is settling at a new steady state value for insolation change within 0.03 s. For the change in insolation from 500 W/m2 to 1000 W/m2, the system is performing vice versa.

C. Dynamic Performance under Varying Temperature

Fig. 7 (a) and Fig. 7 (b) are showing the system dynamic performance for temperature variation from 25 °C to 50 °C and from 50 °C to 25 °C, respectively, at a constant insolation of 1000 W/m2. Since SPV array has a small positive temperature coefficient of current and relatively large negative temperature coefficient of voltage, the change in temperature is increasing the SPV array current (Ipv) slightly but decreasing the SPV array voltage (Vpv) substantially. This is resulting in reduction of SPV array power (Ppv). The motor speed (ωm), load torque (Tl) and loadpower (Pl) are also reducing accordingly and reaching steady state value within 0.03 s. The system performs vice versa when the temperature is restored from 50 °C to 25 °C.

V CONCLUSIONS

A SPV array fed SWP system using VSS-INC method for MPPT and MVC for speed control of PMSM, is implemented and performance has been analyzed through MATLAB simulation and hardware validation. Simulated and experimental results for starting, steady state and dynamic performances have been found to be quite satisfactory. With the use of VSS-INC technique, neither the steady state nor the transient performance is compromised as in conventional INC. The MVC has improved the torque response. The introduction of feed-forward term has accelerated the overall response of the system. No steady state oscillations are observed and faster response has made the system more effective. Detailed comparative analysis has proven the superiority of this control over existing conventional control.

The use of PMSM for driving the pump, has increased the system efficiency and has reduced the system size. The use of single stage topology has eliminated intermediate stage DC-DC converter and reduced the number of components, consequently resulting in reduction of cost, complexity and further increase in the system efficiency and compactness. Simulated and experimental results have found to be quite acceptable and thereby validated the practical feasibility of the system.

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