Performance Evaluation of Switched Reluctance Motor PWM Control in PV-fed Water Pump System

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Abstract- Variable speed drives for PV-fed water pumping system (WPS) in rural areas prove highly promising for economic and social growth. Being more economical without winding and permanent magnets on rotor, switched reluctance motor (SRM) is emerging as an attractive option in variable speed drives. Such a system demands for a suitable controller with simple and reduced components. This paper presents the essence of SRM PWM technique over single pulse mode (SPM) in PV-fed WPS. Performance characteristics such as: torque ripple, phase peak current and DC-link current of the SRM PWM technique tested at various insolation levels are presented in this study. These performance assertions reveal that the PWM technique of SRM outweighs SPM control in PV-fed WPS with reduced torque ripple, reduced peak currents and reduced current gradients. For this study, a 2.2kW 8/6 SRM has been used to build a look-up table based simulation model for SRM in Matlab/Simulink. The system is then implemented using high parallel computing FPGA Spartan 3AN board.

Keywords: FPGA, Pump, PV, PWM, Switched reluctance motor, Variable speed drives.

1. Introduction

Water resources play a prominent role in agriculture. In India, approximately 65-70% of the population lives in villages, which depend on agriculture as a major occupation. Only 54.5% of the villages are with electric supply and more than 1,00,000 villages are yet to be supplied electricity. About 22% of electricity generated is used for agricultural sector. Currently, electricity generation in India is dominated by thermal (63% consisting of coal, oil and natural gas), followed by hydro-generation (25%), and nuclear power (3%) [1][2]. Extending the grid supply to these remote rural areas would be capital cost-intensive and inefficient (losses due to generation, transmission and distribution). In addition, non-renewable nature of thermal power and carbon emission demands for clean alternative energy sources (AES) such as; biomass, solar, wind and hybrid. Currently, these sources contribute about 9% of India's energy requirements [2]. Small scale AES for rural areas promise to reduce burden on grid and produce clean energy as well [3][4]. These sources (solar PV, wind, PV-Wind hybrid) are useful to meet the demand for water pumping requirements for agriculture.

With expected cost reduction in Solar PV array, PV-fed WPS have received increasing interests recently. In this context, wide initiatives are taken-up by ministry of new and renewable energy (MNRE) to develop rural India [3]. Presently, conventional electrical motors (induction motors, synchronous motors, permanent magnet synchronous motors and permanent magnet DC motors) are used for WPS. A viable promising cost effective alternative to these conventional motors in these small scale rural applications is switched reluctance motor (SRM) [5][6][7]. Table 1 describes the comparison of variable speed drive SRM with induction machine and permanent magnet machine based on various criteria [5]. SRM provides better flat-efficiency (over wide speed range) when compared with permanent magnet machine [6]. Compared to conventional machines, SRM offers simplified construction due to the absence of permanent magnets and conductors in the rotor, which results in reduced cost. The authors [7] have presented the advantage of lower environmental effect and longer life cycle of SRM in comparison with IM drives. In the absence of slip rings, carbon brushes, cage bars and commutators, SRM has emerged as a suitable option for wide variable speed drive applications as hand fork, train air conditioner and aerospace [8]. From the above discussion, it is evident that suitable SRM controller for torque ripple minimization and component reduction are essential needs in PV-fed water pumping system operating at various insolation levels.

Table 1. Variable Speed Drive System Comparison [5]

Criteria	Induction Machine	Permanent Magnet Machine	Switched Reluctance Machine
High starting torque	1	3	3
Cool rotor	1	3	3
Maximum speed	2	1	3
Maximum speed range: base to top speed ratio	2	1	3
High peak efficiency	1	3	2
Flat efficiency over a wide speed range	1	2	3
Robust, fault tolerance	1	1	3
Loss of controls / effect of back Electromotive Force (EMF)	3	1	3
High temperature capability	3	1	3
Noise, vibration	3	3	2
Torque ripple	3	2	2
3-Best 2-Average 1-Worst			

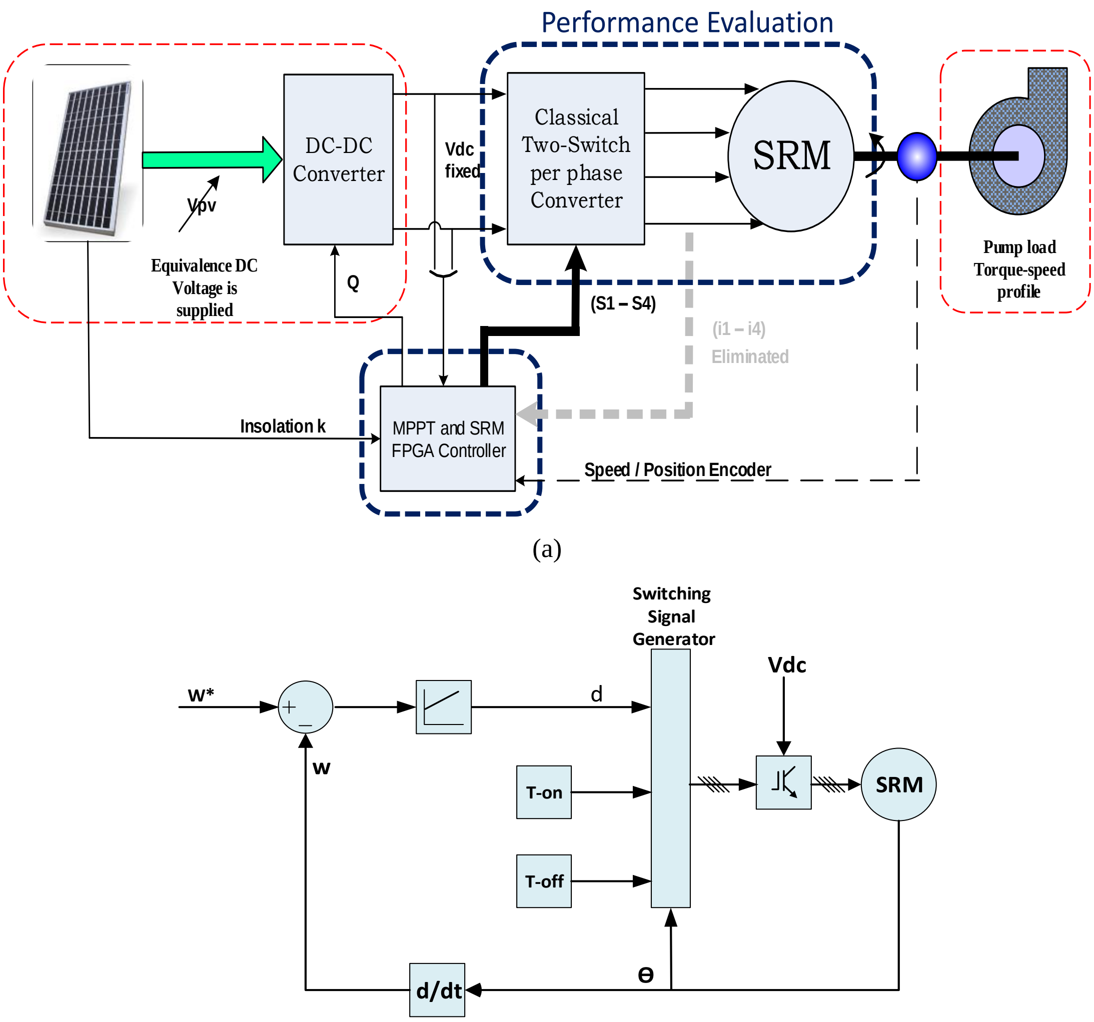


Fig. 1. (a) SRM based PV-fed water pump system (b) SRM PWM control scheme

Some authors have proposed and addressed the application of SRM for PV-powered WPS [8-10]. Deepak Ronanki et al. [8] have proposed direct torque controlled (DTC) SRM drive powered by PV, where control of flux and hence torque and its ripple using hysteresis band control were presented. Classical converter topology was employed to illustrate the DTC for SRM. Sweta Belliwali et al. [9] presented modelling and simulation of direct coupled SRM based PV WPSs. Hysteresis band based torque controller with (n+1) switch converter is proposed. Although hysteresis control aids for torque ripple reduction with additional control schemes, it suffers with additional circuitry of frequency limiters, current sensors, current limiters, and also increase in complexity of controller. Hamid M. B. Metwally et al. [10] have studied the SRM drive performance analysis in PV pumping systems. Matching efficiency between the proposed system and PV array was found to be around 95% with an operating efficiency of 85% most of its working time. Single pulse mode suffers with the higher peak currents and higher current gradients during commutation due to full voltage. In contrast to hysteresis and SPM, PWM offers simplified control, reduced components and lesser current gradient with possibility of full or zero voltage during commutation. Hence, its significance in specific with PV-fed WPS has to be studied, analysed and compared.

This paper presents the essence of SRM PWM control in PV-fed WPS and its steady state performance characteristics at various insolation levels. Steady state performance characteristics of torque ripple, phase peak current and DC-link current tested at various solar insolation levels have been presented. A 2.2kW 8/6 3000 rpm SRM is used for simulation and experimental validation of the system. Followed by introduction in section I, section II presents FEM modelling of SRM flux-linkage characteristics and its experimental validation. Among most wide used SRM controls such as: hysteresis, single pulse and PWM technique, the advantage of PWM over hysteresis and angle control in PV-fed WPS is explained in section III. Section IV presents the simulation, implementation and experimental results validation of PWM and its performance characteristics at various insolation levels.

2. PWM Control Strategy of SRM in PV-fed Water Pumping System using FPGA

SRM is gaining wide importance in rural off-grid applications. The authors [11] have presented the state of art review on control strategies and suitability of SRM for off-grid applications such as PV WPS, wind energy conversion system and hybrid PV-wind system. In general, SRM conventional control strategy requires chopping control at low speeds and angle control at higher speeds. In lower speed chopping control range, control parameters are I_{ref}*, Ton and Toff angles. At higher speed angle control range, only two parameters T_{on} and T_{off} angles would suffice to meet the required torque demand. Hysteresis based controller needs control reference currents to meet the required torque levels. Thus, it requires current sensors and frequency limiter for each phase to perform band control over I_{ref}. Hysteresis band and sensors can be eliminated by using fixed frequency PWM switching of phase voltage to meet the required torque levels [12-14]. Although single pulse mode offers same advantages as of PWM over hysteresis, PWM technique will result in additional possibility of full or zero voltage during commutation which further adds to noise reduction. The following are the advantages of PWM technique

- Elimination of hysteresis band current feedback sensors.
- Elimination of frequency limiters.
- In contrast to single pulse mode, it offers possibility of full or zero voltage during commutation, hence further aids for reduction in noise levels.
- Simple duty cycle based PWM control.

A PV-fed WPS system demands for reduced components and better performance using suitable simple controller for the motor. Although hysteresis control is suitable for the SRM based PV-fed WPS, it suffers with additional circuitry of current sensors, frequency limiters due to band, current limiters and complexity in control scheme. Among the two current sensorless control schemes (PWM and SPM), a comparison of performance indices such as: torque ripple and peak current has to be studied in SRM based PV-fed WPS operating at various insolation levels for the evaluation of suitable controller. Fig. 1(a) and 1(b) shows the block diagram representation of SRM based PV-fed water pumping system and its PWM based control scheme. In this work, SRM PWM control performance evaluation is studied at various operating insolation levels using pump load profile in comparison with SPM. The control technique can be realized using FPGA technology because of its fast realization of non-linearity in SRM with parallel computational ability as compared to conventional DSP [15-17]. Authors [17] have presented the flexibility and benefits of using FPGA over DSP for SRM control. The advantages of FPGA over DSP, such as hardware flexibility, functionality, parallel architecture, scalable hardware, flexible pin assignment etc., have already been explained. FPGA based hysteresis control for SRM was developed and tested on SRM model emulated in real time RT-Lab [18]. In this work, PWM control strategy of SRM for PV WPS is simulated and implemented using FPGA technology. In general, the varied voltage to fixed DC bus voltage is maintained by intermediate chopper. A simple PWM technique with fixed voltage is used to realize speed control referenced by maximum power point.

3. Simulation and Implementation

3.1 PV array and pump load

The PV array used in this study consists of 18 parallel strings, 975 cells in series per string, such that the overall terminal voltage v_{array} and P_{array} at ambient temperature is given by [21-23].

$$v_{array} = 70.176 * log_e\left(\frac{I_{ph}-I_{array} -0.09}{0.09}\right) - 2.708 * I_{array} \ldots\ldots \quad \ldots(1)$$

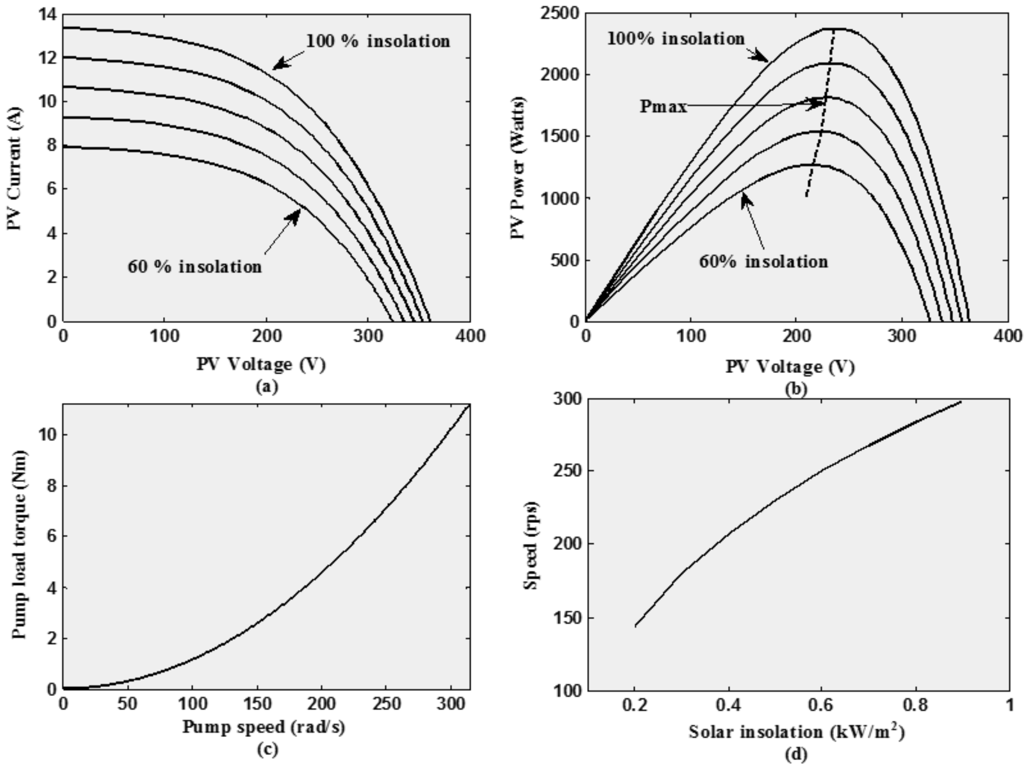


Fig. 2. PV and pump characteristics (k), (a) Current-voltage curves, (b) Power-voltage curves

(c) Pump-load characteristics and (d) reference speed at P_{max}

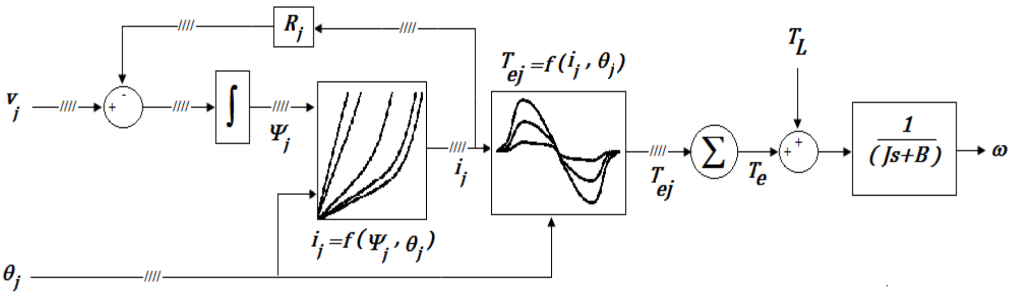


Fig. 3. Model of SRM based on Look-up table

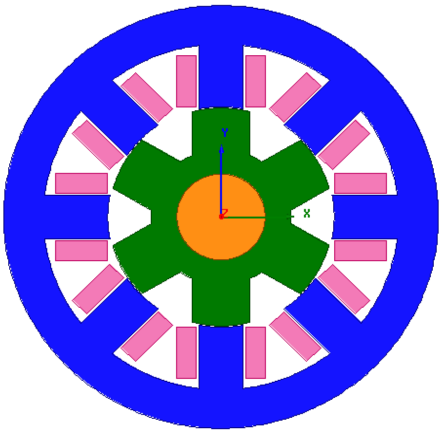
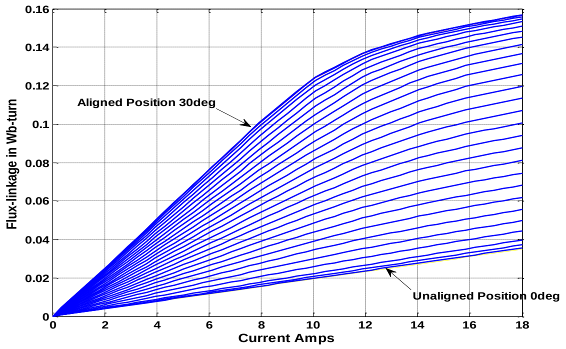
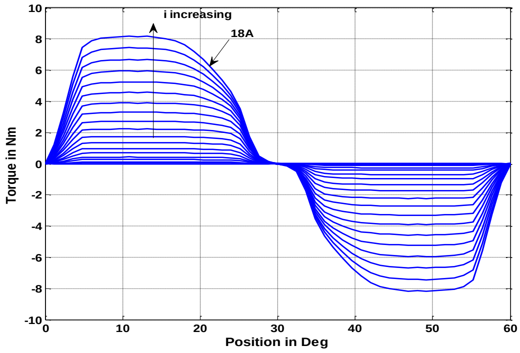


Fig. 4. ANSYS MAXWELL model of 8/6 SRM

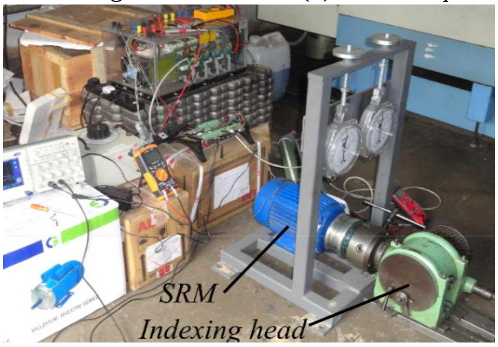


(a)

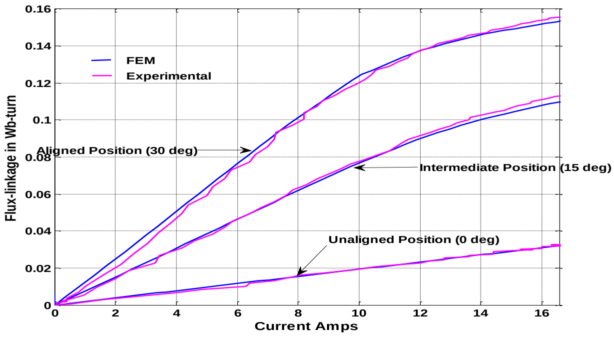


(b)

Fig. 5. (a) Flux-linkage characteristics (b) Static torque characteristics

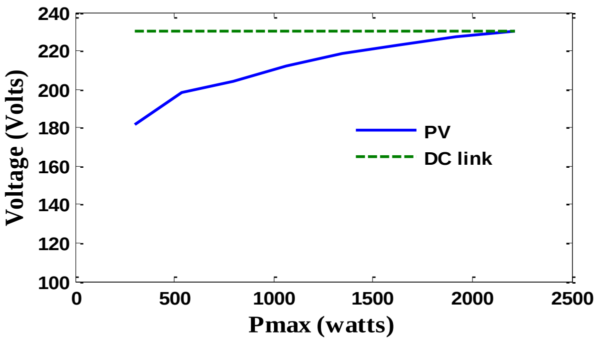


(a)

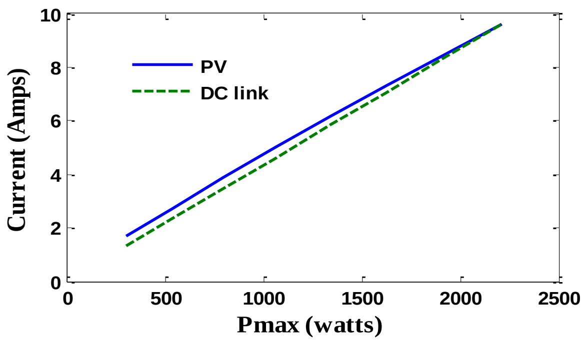


(b)

Fig. 6 (a) Experimental setup to determine flux-linkage characteristics
(b) FEM and experimental determined flux-linkage characteristics



(a)



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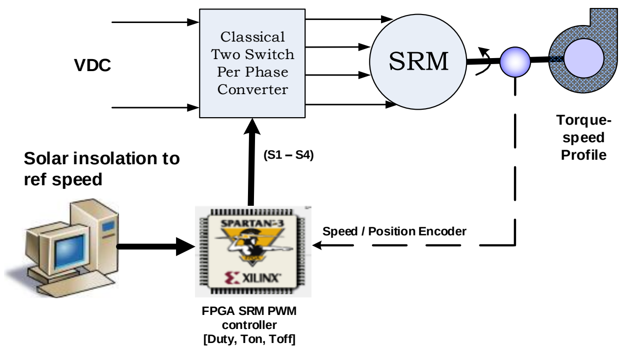
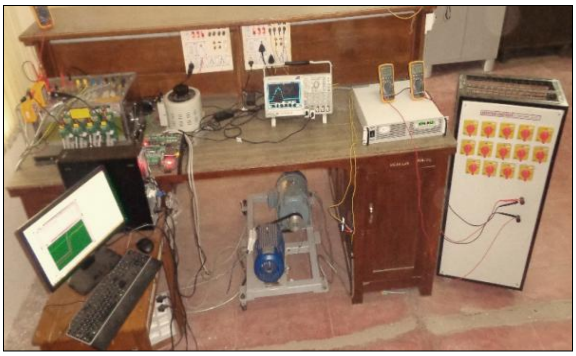
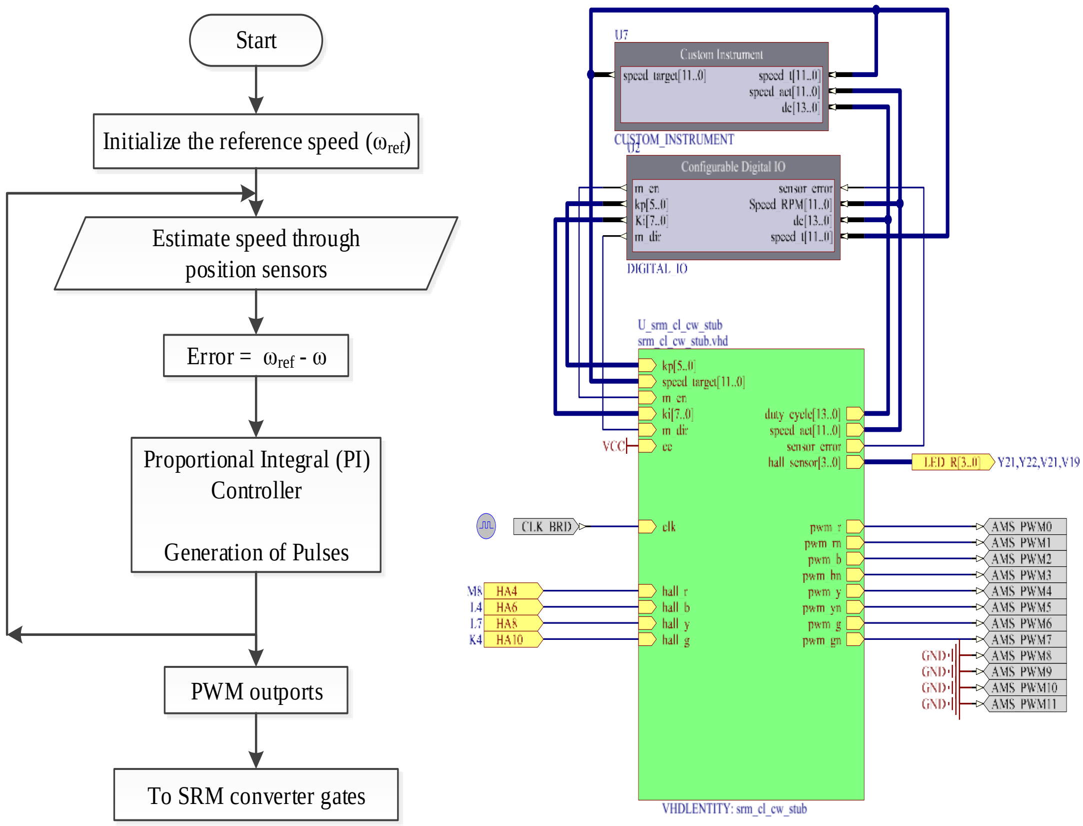




(c)

(d)

Fig. 7 (a) PV and fixed dc voltage characteristics (b) PV and DC-link current at various P_{max}
(c) Block diagram of experimental setup (d) Experimental setup of the system



(a) (b)

Fig. 8. (a) Flow chart of algorithm (b) Altium-designer schematic of control algorithm

$$P_{array} = 70.176 * I_{array} * log_e\left(\frac{I_{ph} - I_{array} - 0.09}{0.09}\right)$$
$$-2.708 * \left(I_{array}{}^{2}\right) \quad \ldots\ldots \quad \ldots(2)$$

Where I_{array} is the PV array current, I_{ph} is the insolation dependent photocurrent. For centrifugal pump load along with friction is considered as given Eq. (3) and (4).

$$T_L = 0.025 * \omega + 0.000570 * \omega^2 \quad \ldots.. \quad \ldots.. \quad ..(3)$$

$$P_L = 0.025 * \omega^2 + 0.000570 * \omega^3 \quad \ldots\ldots\ldots. \quad ..(4)$$

Where, at PV maximum power point, the approximate reference speed can be computed by solving the following expression:

$$P_L = \eta * P_{max} \quad .. \quad ..(5)$$

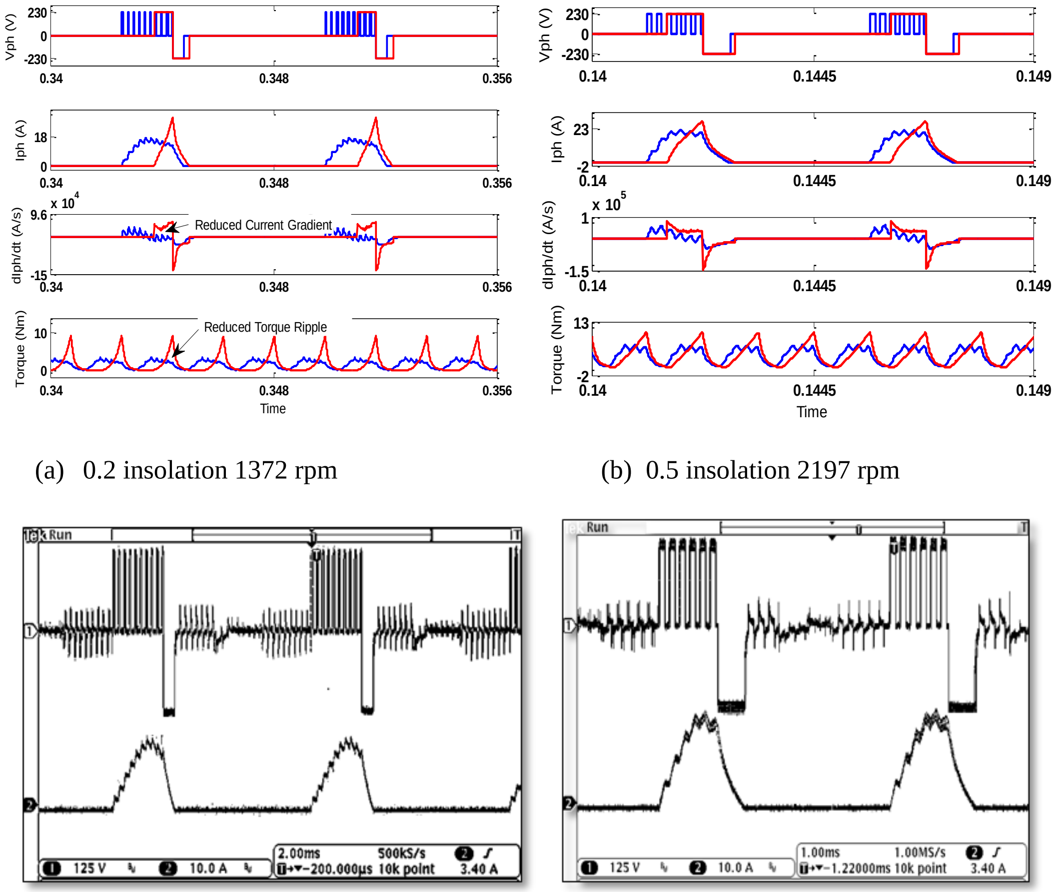
$$0.00057 * \omega^3 + 0.025 * \omega^2 - \eta * P_{max} = 0 \quad \ldots \quad .(6)$$

Fig. 2(a) and 2(b) depicts the PV current, power and maximum power characteristics w.r.t voltage at various insolation levels. Fig. 2(c) shows the torque-speed characteristics of pump load considered. Fig. 2(d) shows the reference speed at P_{max} computed from equation (6). With this pre-computed reference speed for various insolation levels, the SRM PWM and SPM control schemes are tested and analysed at these insolation levels. The objective of this work is to study performance features control such as torque ripple and peak current at various steady operating insolation levels for SRM using PWM and SPM. The motor is supplied with the voltage corresponding for speed control operating at maximum power for a insolation with the speed torque profile considering of pump type load. Both the PWM and SPM scheme are compared for their torque ripple and peak current at various insolation levels.

3.2 Switched Reluctance Motor

In modelling and control of SRM, flux-linkage characteristics play a vital role. Hence, it demands to determine the non-linear flux-linkage characteristics. Generally, two approaches are used to obtain these characteristics, one is the Finite Element Method (FEM) and the other is the experimental approach through direct measurement. Simulation model for SRM as depicted in Fig. 3 can be built based on look-up table's approach [11]. This approach consists of look-up tables with the current characteristics *i* (ψ, θ) and the static torque *T* (*i*, θ) which are populated by FEM or experimental data. In this work 2.2kW 8/6 3000RPM SRM machine dimensions are used and its ANSYS MAXWELL model is developed as shown in Fig. 4.

Also, its flux-linkage and static torque characteristics are generated using ANSYS MAXWELL as depicted in Fig 5(a)



(a) 0.2 insolation 1372 rpm

(b) 0.5 insolation 2197 rpm

(c) 0.2 insolation 1372 rpm

(d) 0.5 insolation 2197 rpm

Fig. 9 (a) & (b) Simulated @0.2 kw/m^2 1372 rpm & @ 0.5 kw/m^2 2197 rpm
(c) & (b) Practical @0.2 kw/m^2 1372 rpm & @ 0.5 kw/m^2 2197 rpm

and Fig 5(b) respectively. It is required to validate the flux-linkage characteristics developed by FEM in order to obtain an accurate model. The experimental method to determine flux-linkage characteristics, which make use of rising current method as the basis is used to validate FEM flux-linkage as shown in Fig 6(a). Fig. 6(b) shows that the flux-linkage characteristics determined at 0 deg (unaligned), 15 deg (intermediate) and 30 deg (aligned) which are in close agree with the FEM characteristics.

3.3 Implementation

A 2.2kW 8/6 3000RPM SRM machine with classical two switch per phase converter is used for this study. As the objective of this case study is to evaluate performance of SRM PWM control over SRM SPM control in PV-fed WPS, fixed DC voltage (FDC) of 230V is considered from variable PV source voltage which is intermittent in nature and is dependent on PV array characteristics by using equal power-levels. The current levels for fixed voltage by means of equal power balance are illustrated in Fig 7(a) and 7(b). The correspondent equivalent current drawn with fixed voltage at the same maximum power point for an insolation. For each insolation level the SRM PWM and SPM control are compared for their torque ripple and peak current. SRM is provided with hall sensors for position information from which rotor position and speed can be computed. With the position information, turn-on and turn off angles (Ton and Toff) are fixed and SRM is operated in PWM control mode at different reference speeds and their corresponding torque levels using pump speed-torque profile. For SPM Ton is varied to achieve required torque level for a speed with fixed Toff. Fig. 7(c) and 7(d) shows the block diagram and experimental setup of the SRM based PV-fed WPS. Both the control techniques are built using Altium-Nanoboard with FPGA Spartan 3AN. Altium software is used to build control logic and interface between PC and board. Fig. 8(a) & 8(b) depict the control algorithm and its schematic respectively. For FPGA implementation, this strategy is modelled and simulated in Matlab/Simulink environment using Xilinx System Generator and is realized in Xilinx Spartan-3AN nanoboard.

4. Results and Discussion

The simulation model built in Matlab/Simulink is used to compare both the PWM and SPM control at various insolation levels. Fig. 9(a) shows the simulated PWM and SPM technique at 0.2 insolation (1372 rpm) with T_{on}= -3.75 deg and T_{off} as 11.25 deg. In case of SPM T_{on} is varied and

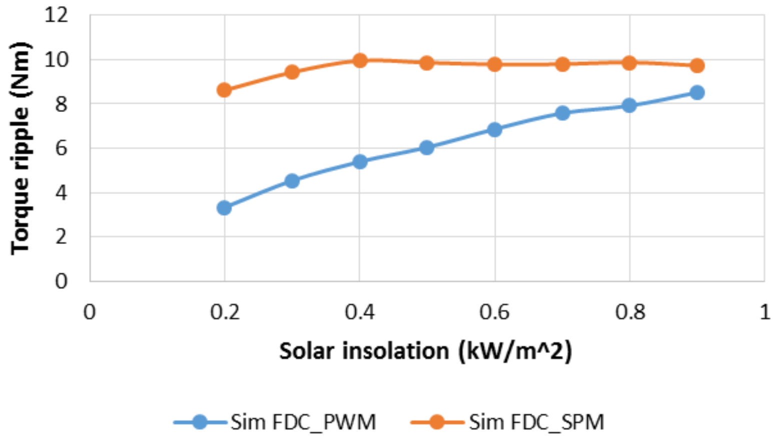


Fig. 10. Torque ripple comparison of PWM and SPM at various insolation levels

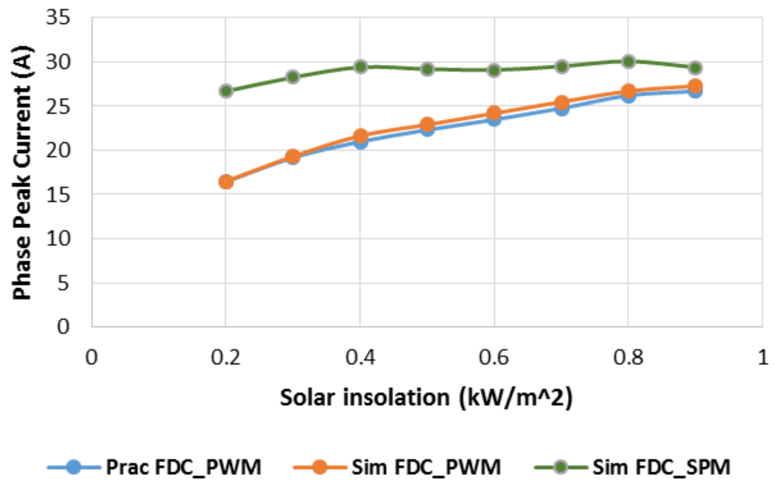


Fig. 11 Simulation and experimental comparison of phase peak current

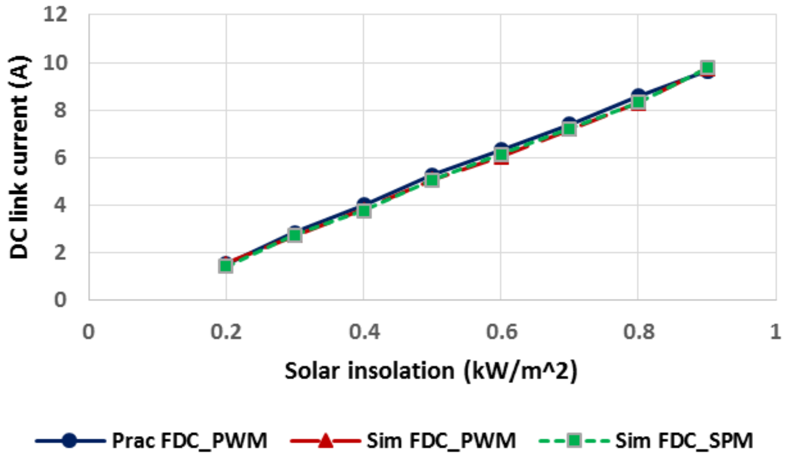


Fig. 12 Simulation and experimental comparison of DC link current drawn

at MPPT at various insolation levels

T_{off} is kept fixed at 11.25 deg. It can be observed that PWM control provides reduced current gradient during commutation, reduced torque ripple and reduced peak current when compared with SPM technique. With such key advantages, PWM technique for SRM is implemented for different speeds with varying duty cycle to achieve torque levels as per pump characteristics shown in Fig 2(c). SRM control is tested for its performance of torque ripple and peak current operating at various insolation levels. Fig. 9(a) & 9(b) shows the simulated phase voltage and current at 0.2 and 0.5 insolation operating at 1372 rpm and 2197 rpm respectively. Fig. 9(c) & 9(d) shows the experimental phase voltage and current at 0.2 and 0.5 insolation operating at 1372 rpm and 2197 rpm. Results show that the experimental approach is in good agreement with the simulation model. It can be observed from Fig. 10 that the torque ripple in PWM technique is less when compared to SPM control at various insolation levels (operating range of 0.2 to 0.9 kW/m^2). From Fig.11 it can be observed that PWM technique offers lower phase peak current values as compared to SPM. Operating at various insolation levels with pump characteristics, the SRM based system should be justified with the maximum power point DC link current drawn as depicted in Fig 7(b). Fig. 15 shows the simulated and experimental DC link current at various insolation levels, which is compared to the simulated SPM. From Fig.15, it is found that there is a close agreement of experimental and simulation results with that of theoretically calculated DC current at maximum point at various insolation levels as shown in Fig 7(b). From these results SRM operating with PWM and SPM with reference speed at various insolation levels with maximum power, it is evident that PWM control provides lesser torque ripple and lesser peak current over wide range of insolation levels.

5. Conclusion

This work presents essence, modelling, simulation, FPGA based implementation and performance evaluation of SRM PWM control strategy in PV-fed WPS. This strategy eliminates the necessity of current sensors, frequency limiters and current limiters as compared with hysteresis control, thus enabling the PV-fed SRM WPS more cost-effective and saving much on area. Although, the SPM control has similar advantages, PWM control strategy would result in the possibility of zero or full voltage during commutation, which reduces the current gradient, further lowering the noise. With such advantages, PWM strategy in PV-fed WPS system has been studied for its performance parameters such as torque ripple and peak current at various insolation levels. These comparative assertions convey that PWM technique results in reduced torque ripple which further reduces the system noise in contrast to SPM for various insolation levels. With the advent of FPGA with higher parallel computational ability, this work presents the implementation of PWM technique for PV-fed WPS using Spartan 3AN FPGA on 8/6 2.2kW SRM. Experimental results are found in congruence with the simulation. As this work presents the study of performance characteristics of SRM control in PV-fed WPS using PV and pump characteristics points, further with actual PV and pump using PWM control would be a future scope to study.

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