Essence of Variable DC PWM Control for Switched Reluctance Motor in Direct PV-fed Water Pump

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***Abstract*— Switched reluctance motor (SRM) has emerged as an viable option in variable speed drives because of its various benefits such as high power density, high efficiency, and thermal robustness. Without the winding or permanent magnets on rotor makes it cost effective. This paper presents essence of Variable DC (VDC) PWM based control for SRM in Direct PV-fed Water Pumping System (WPS). The technique provides reduction in noise due to reduced current gradients during commutation as compared to angle control strategy. In addition, current sensors used in hysteresis control and intermediate DC-DC converter for MPPT are eliminated which results in reduced costs. A Matlab/Simulink look-up table simulation model is developed using experimentally determined flux data to study the effect of proposed system on phase currents and duty cycle is presented. The control is implemented using FPGA Spartan 3AN board. The results of simulation and implementation validate the control and are found in agree.**

Keywords— ***PV, PWM, Rural, SRM, Variable Voltage Control, Water Pump.***

I. Introduction

Extending grid to remote standalone rural areas would be capital cost-intensive and less efficient (due to losses in transmission and distribution). Further, depletion of thermal fuels and carbon pollution demands for clean alternative energy sources (AES) such as; solar, wind, biomass and hybrid. Currently, these sources add about 9% [1]-[3]. These small scale AES for rural areas are beneficial to produce clean energy and reduce burden on grid as well. These sources are useful to meet water pumping for household in rural. Presently, conventional electrical machines (IM, SM, PMSM and PMDC) are used for water pumping system (WPS). A promising cost effective higher efficiency viable alternative to these machines in these remote rural applications is SRM. With its wide advantages such as; simple construction with no winding or magnet on rotor, higher efficiency, and high power density ratio etc., SRM has emerged as an attractive option for variable speed drives applications. With no permanent magnets or winding on rotor makes it economical. Its low cost and good performance features makes it a subject of research interest in academics as well as industries [5]-[11]. SRM as a low cost variable speed drive is well established since three decades and has found its suitability in wide applications such as rail air conditioners, traction, aero generator etc. Hence, there is a wide scope of research to develop and to study the significance of SRM control schemes in direct PV-fed WPS.

This paper mainly addresses the performance significance of variable DC based PWM control for Switched Reluctance motor in direct PV-fed WPS. Section II introduces SRM modeling, converter and control strategy. Section III presents significance of based variable DC voltage concept for SRM PWM control and its advantages over conventional schemes in Direct PV-fed WPS. Modeling, Simulation and results are discussed in section IV. Section V presents the conclusions of the work.

II. Switched Reluctance Machine

The construction features of SRM differs from the conventional motors. It consists of salient poles on both the stator and rotor constructed from laminations. Windings are on stator, while rotor does not hold any winding or permanent magnet [5][6]. An 8/6 pole configuration SRM is considered to explain the construction of the SRM. The cross-section of an 8/6 pole SRM is shown in Fig. 1(a) and it can be observed that the construction of SRM is simple. Fig. 1(b) depicts the flux-linkage curves of 8/6 pole SRM. Fig. 3 shows the most widely used SRM converter topologies. Considering two switch per phase classical converter topology of SRM as shown in Fig 2(a), when a particular phase PhA is excited, the flux in that phase will tend to align the nearest rotor pole along the corresponding excited stator pole from unaligned maximum reluctance position to aligned minimum reluctance position. Thus, this principle of torque production is known as reluctance. At the aligned position the magnetic path exhibits higher degree of saturation as depicted by curve 1 in Fig. 1(b). At the unaligned position the magnetic path will have higher reluctance due to large air gap and hence not susceptible for saturation. The flux-linkage characteristics in unaligned position is shown by curve 3 in Fig 1(b). Any other position between aligned and unaligned will have the characteristics curve between that of unaligned and aligned positions as shown by curve 2 in Fig. 1(b). Considering the converter as shown in Fig. 2(a), when the two transistors are ON, the governing voltage equation is given by [5]-[9]

$$V = i * R + \frac{d\psi}{dt} \qquad (1)$$

Where, V-excitation voltage, i-phase current, R-phase resistance and ψ- flux-linkage. Instantaneous torque is given as;

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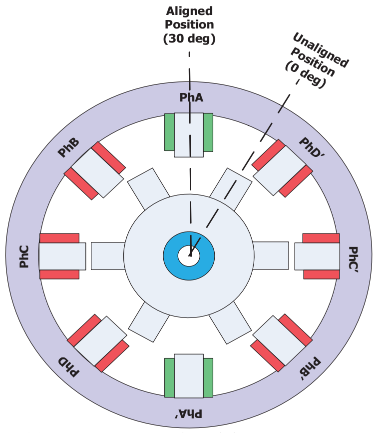
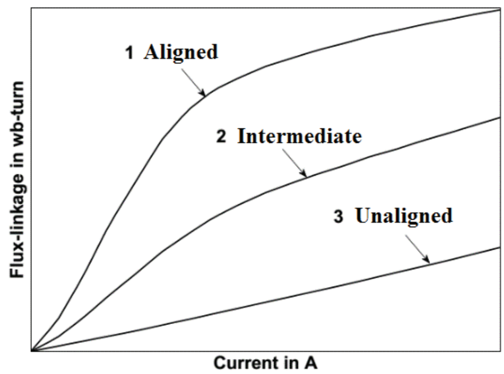


Fig 1. (a) SRM constructional feautures



(b) Flux-linkages curves at various positions

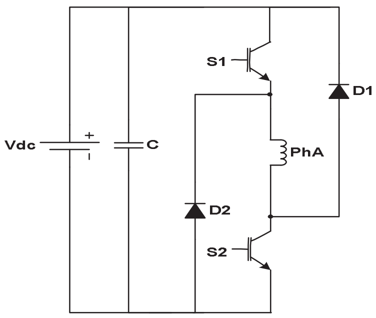
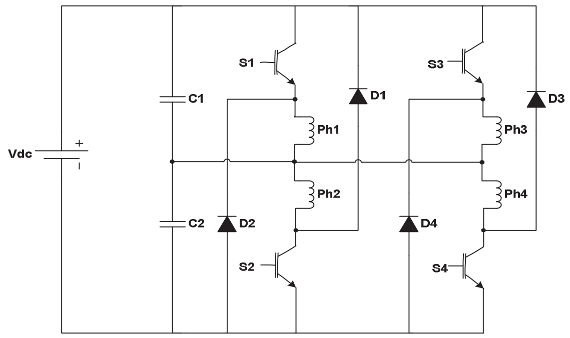


Fig 2. (a) Two switch per phase converter



(b) OULTON Single switch per phase converter

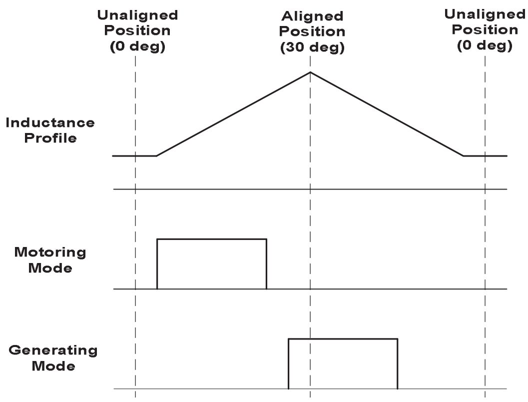
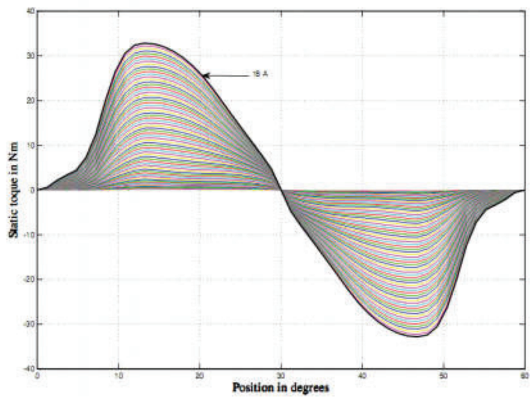


Fig. 3. (a) Switching of phase for motoring and generating torque



(b) Static torque characteristics [7] [8]

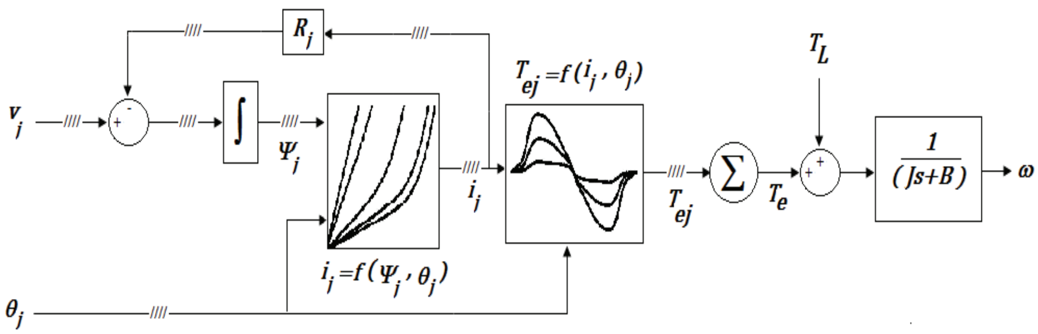


Fig. 4. Look-up table based model of SRM

$$\psi = \int (V - i * R)\, dt \qquad (2)$$

$$w' = \int_0^i \psi\, di \qquad (3)$$

$$T_e = \left.\frac{\partial w'}{\partial \theta}\right|_{i=constant} \qquad (4)$$

where, w' is the co-energy, T_e is the torque and θ is the rotor position. If non-saturation is considered ($\psi = i * L$, where L is inductance) then the torque equation can be simplified as

$$T_e = \frac{i^2}{2}\frac{dL}{d\theta} \qquad (5)$$

It can be observed that from (5), the sign of torque is not dependent of the polarity of current, but rely on the slope of inductance profile. Switching the phase during positive slope of inductance profile results in developing positive torque (motoring mode) as shown in Fig 3(a) and 3(b). For operation of SRM in motoring, the converter topologies are required to excite the phases in line with the rotor position. Various converter topologies are presented in literature for SR-Machine such as two switch per phase classical, , Miller n+1 one switch per phase OULTON, C-dump, resonant, R-dump etc. [5][6]. Among wide range of converter topologies available in literature, two most widely used are classical two switches per phase topology and OULTON one switch per phase topology as shown in Fig. 2(a) and (b). Due to lesser number of switches, it is obvious from the Fig. 2 the switching losses are less in OULTON converter.

Conventional control of SRM can be categorized into low speed chopping mode and high speed angle control mode. At low speeds, back emf is low, if the phase is turned on at unaligned position where the currents can reach very high values by the time rotor reaches aligned position. Therefore at low speeds, the phase current is controlled by chopping. The reference current for chopping depends on torque demand with control parameters as (I_{ref}*, Turn on angle T_{on} and Turn off angle T_{off}). As the speed increases, back emf will increase and would limit the current to fall below chopping reference current levels, so that the torque can be controlled only by varying the only angles of a single pulse of current (T_{on} and T_{off})[5]-[7].

Flux-linkage characteristics play a key role in modelling and control of SRM as its Idealization of the flux-linkage characteristics would result in a model which cannot estimate the performance of the machine with satisfactory accuracy. Therefore, it is necessary to determine the nonlinear flux-linkage characteristics as accurate as possible. Generally two ways are followed to determine the characteristics such as; first is the numerical way followed by finite element method (FEM) and second is the experimental way through direct measurement. Simulation model for SRM from governing equations can be built using look-up table method. This method consists of look-up tables that are populated with the current characteristics $i(\psi,\theta)$ and the static torque $T(i,\theta)$. Fig. 4 shows the look-up table based simulation model of switched reluctance machine [10]-[12].

III. Variable DC Control Strategy For SRM Based Direct PV-Fed WPS

As discussed in section II, SRM conventional control strategy with fixed DC bus voltage demands chopping current control at lower speeds and at higher speeds using angle control. In chopping control mode the control parameters are (I_{ref}*, T_{on} and T_{off}), whereas in high speed angle control mode only T_{on} and T_{off} would serve to meet the required torque demand. Chopping control have the limitation of sensors, higher switching losses and noises. Authors [10][17] suggested a variable DC bus voltage with respect to speed to avoid chopping control at low speeds and operating only in angel control mode throughout the speed range. Varied DC bus voltage angle control mode was achieved using an additional chopper between supply rectifier and SRM converter. This strategy overcomes the limitations of switching losses and noise in comparison with low speed chopping operation. In addition variable voltage strategy provides improvement in position sensorless estimation as shown in Fig. 5. Further, extending this variable DC principle in PWM technique would aid for further reduction in noise levels due to zero or reduced voltage during commutation. These are the following advantages of VDC-PWM technique

- Eliminates current feedback sensors as in case of Hysteresis.
- Further, eliminates the frequency limiters.
- Reduce current gradient levels thus further reducing noise [due to reduced or zero voltage during commutation].

In general, conventional methodology for SRM in PV Water Pumping system, a DC bus voltage is maintained by intermediate converter between PV source and SRM converter as shown in Fig. 5. This chopper output can be regulated in linear with maximum power point reference speed of SRM in this variable voltage control strategy. This variable DC based PWM technique plays promises key element in case of direct PV-fed WPS where the intermediate stage can be eliminated. Hence, the performance significance of this VDC PWM is more essential to study the effect in direct PV-fed WPS. All these schemes are simulated and the significance of VDC PWM is presented in this work. Fig 5 & 6 describe the system, where it can be seen that the scope of the work to eliminate the current sensors and intermediate stage with aid of simple PWM control with better performance.

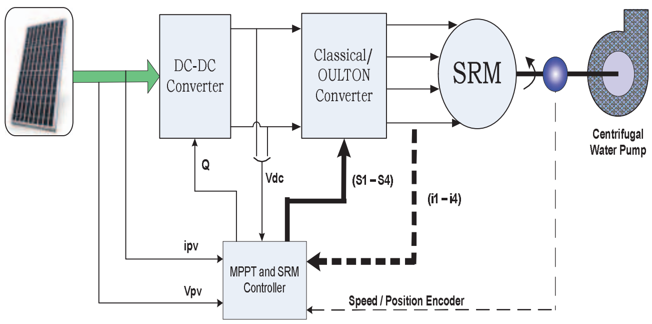


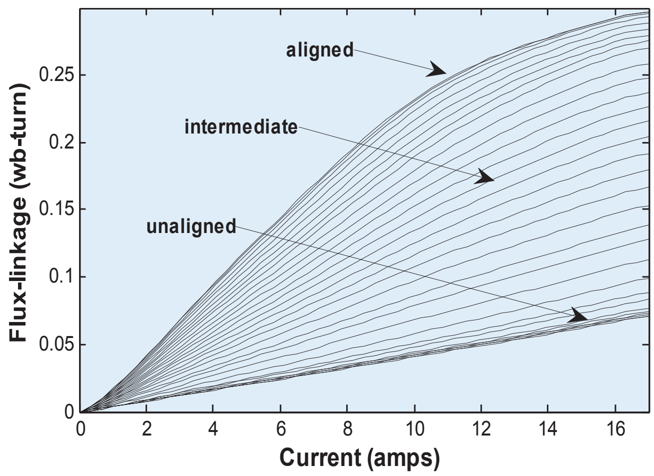
Fig. 5. SRM based PV water pumping systems

IV. MODELLING, SIMULATION AND IMPLEMENTATION

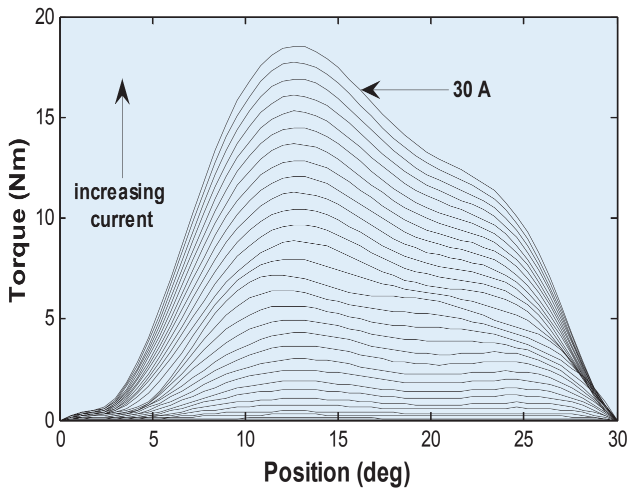
A. Modelling

1) Switched Reluctance Motor:

Simulation model of SRM have been built using LUT based approach based on the governing equations (1) to (5) of electrical and mechanical systems. This method consists of LUT with the current characteristics $i\ (\psi,\ \theta)$ and the static torque $T\ (i,\ \theta)$ which can be established by FEM or experimental data. In this work, experimental approach is used to populate the flux-linkage characteristics and to compute static torque characteristics of an 8/6 3000 rpm SRM. Fig 6(a) and 6(b) shows the experimentally obtained flux-linkage and static torque characteristics respectively.



(a)



(b)

Fig. 6. Experimental computed characteristics of SRM: (e) Flux-linkage curves & (f) Static torque curves

2) PV model:

The PV array considered in this work consists of 10 parallel path strings, 748 cells in series per string, such that the overall terminal voltage v_{array} and P_{array} at ambient temperature is given by [16]

$$v_{array} = 47.3688 * log_e\left(\frac{I_{ph} - I_{array} + 0.005}{0.005}\right) - 1.296 * I_{array} \quad (6)$$

$$P_{array} = 47.3688 * log_e\left(\frac{I_{ph} - I_{array} + 0.005}{0.005}\right) - 1.296 * (I_{array}{}^2) \quad (7)$$

where I_{array} is the array current, I_{ph} is the insolation dependent photocurrent.

3) Pump load:

A centrifugal pump load is considered for simulation studies with the governing equations (8) and (9). Fig. 9. shows the pump load characteristics.

$$T_L = 0.00103 * \omega^2 \quad (8)$$

$$P_L = 0.00103 * \omega^3 \quad (9)$$

B. Simulation

All the three basic schemes (i.e., hysteresis, angle and PWM) are simulated and tested for fixed and linear speed-voltage characteristics and then direct PV voltage. For hysteresis mode I_{ref} value is varied such that the SRM with pump operates at the steady state P_{max} power being excited by FDC, VDC and precomputed V_{max} for various solar insolation levels as indicated in Fig.8.

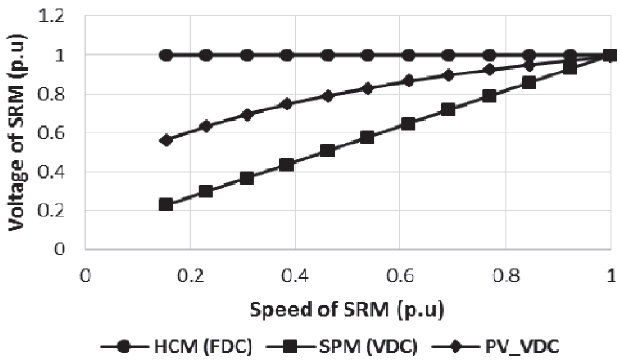


Fig. 7. Voltage versus speed curves of proposed system with various control schemes

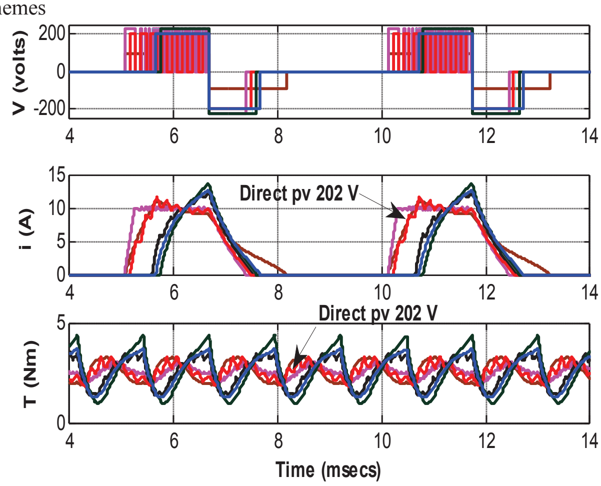


Fig. 8. Simulated phase voltage, current and resultant torque for hysteresis, angle and PWM controls (FDC=230V, VDC=98V and Vpv=202V) at 1977rpm and 2.5Nm @insolation of 0.4kW/m²

B. Implementation

From the simulation results as shown in Fig. 9 it can be confined the PWM technique with variable DC of direct PV fed is offering less peak current, near same rms and lower torque ripple and hence low noise. Therefore, Direct PV voltage fed with PWM technique is studied at various insolation levels and further compared with that of simulations. A 2.2kW 8/6 3000RPM SRM machine with classical converter is used in this work. From the obtained characteristics a lookup table based simulation model of SRM is built in Matlab/Simulink. Initially, With T_{on} and T_{off} fixed SRM is operated in conventional fixed voltage PWM control mode for different speeds and torque levels. The torque levels are loaded on shaft using DC generator coupled. Then the VDC system is simulated for various speeds with varying duty cycle to attain torque levels. Both FDC, VDC control schemes are implemented and tested using FPGA Spartan 3AN board with classical two switch per phase converter. Altium Designer software is used to develop control logic and also as interface between PC and board. One of the key feature of using FPGA is its fast realization of non-linearity in SRM with parallel computational ability as compared to conventional DSP. For FPGA implementation, this strategy is modeled and simulated initially in Matlab/Simulink environment using a Xilinx System Generator and is realized in Xilinx Spartan-3AN nanoboard. Comparison of phase rms and peak currents for both FDC and PV VDC strategy are presented. Fig. 10 to 12 depicts the simulated and experimental voltage and current at 0.2 kW/m^2 for both FDC and direct PV. Fig. 12 & 13 shows the characteristics curves of DC link current and rms values for both schemes at various insolation levels.

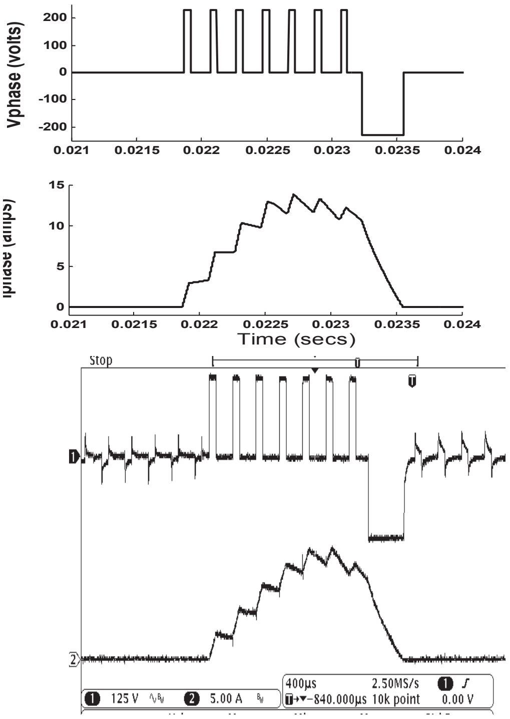


Fig. 9. Simulated and experimental phase voltage and current at 0.2kW/m^2 (1372 rpm) FDC=230V (duty 0.2739)

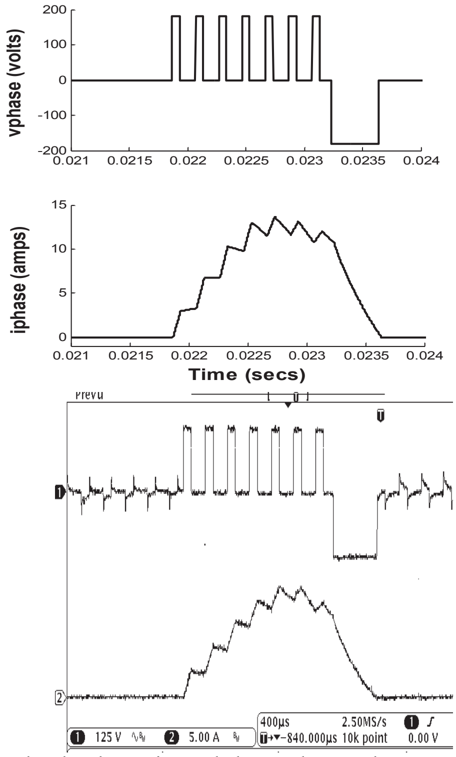


Fig. 10. Simulated and experimental phase voltage and current at 0.2kW/m^2 (1372 rpm) Vpv VDC=181V (duty=0.3412)

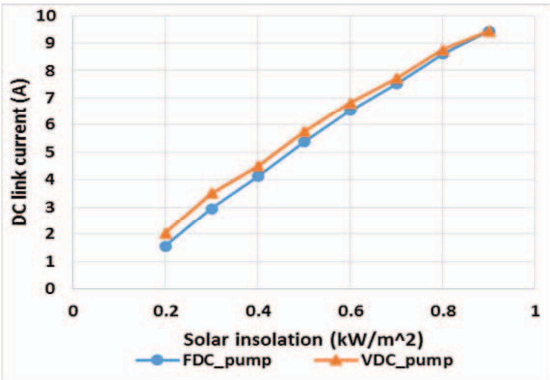


Fig. 11. DC-link current for FDC 230V and Vpv variable DC at various insolation levels

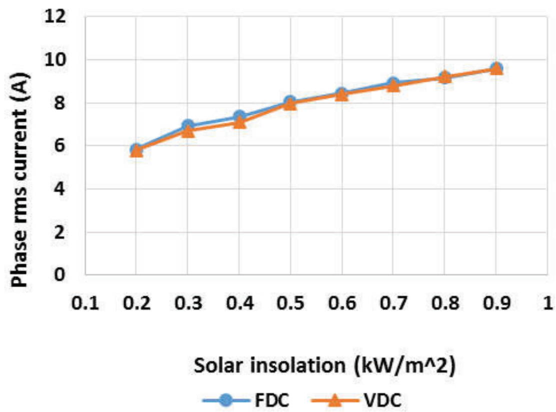


Fig. 12. Phase rms current for FDC 230V and Vpv variable DC at various insolation levels

V. CONCLUSIONS

With its wide advantages such as high efficiency, low cost, high torque to weight ratio etc. SRM is gaining research importance in wide variable speed drive applications. In this work, essence of using variable DC principle based PWM technique for SRM in direct PV-fed WPS is presented. It offers various merits in the direct PV-fed SRM WPS;

- Elimination of hysteresis band current feedback sensors which are needed in hysteresis control.
- Elimination of frequency limiters.
- Reduction in current gradient levels thus further reducing noise [due to reduced or zero voltage during commutation compared to VDC angle control].
- Results in lower torque ripple when compared to fixed DC PWM, hysteresis and angle control.
- From results we can observe that it can be operated on direct PV voltage levels with near same rms and draws the the DC-link current corresponding to same power levels. Thus, aids in eliminating the intermediate power stage. Results in reduced components and control complexity.
- PWM based control can be directly used for MPPT at various insolation levels.

With these key features variable DC principle with PWM technique exhibits good potential in direct PV-fed SRM WPS. The system was modelled in Matlab/Simulink environment and implemented using FPGA control board. The experimental results are found in agree with simulation.

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