Design and Implementation of ZETA Converter Fed SRM Drive Based PV system for Agricultural Applications

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Abstract

In this article the design of Photo-voltaic (PV) based ZETA converter has been presented to drive the Switched Reluctance Motor (SRM) for the agricultural based applications to pump the water. PV panels are the major power resource to supply a water pump driven by 8/6 SRM motor. A Perturbation & Observation (P & O) based maximum power point tracking (MPPT) scheme is adopted to improve the performance of PV system. A dc-dc ZETA is connected in between PV and SRM drive to provide steady and continuous supply to the SRM for efficient operation of the system. The variable DC-link capacitor voltage of the ZETA converter controls the speed of SRM drive from various environmental conditions and irradiation levels of solar PV array. ZETA converter has the added advantage over other types of buck-boost converters is that, it does not require added circuitry for inrush current problem and overload protection is also not required. To reduce the stresses on the converter elements, the two inductors are chosen to operate in continuous current conduction mode (CCM). A four-phase 8/6 SRM drive is developed in the MATLAB/SIMULINK environment to demonstrate the effectiveness of specified system.

Keywords: Solar PV system, MPPT, ZETA converter, SRM drive, agricultural applications, Perturbation and Observation (P&O)

I. Introduction

The PV array price is falling all the time, making PV power production cheap and viable. It has many benefits like environmental friendly, no harmful waste, and last for many years with little maintenance. With these merits, PV systems have huge integrity in the isolated locations to provide electrical supply for lighting, house/agricultural water pumping, telecommunications, etc. [I]. Nowadays, many researchers are working on the PV based water pumping system for house hold and/or
agricultural applications. This system generally contains a PV panel arrangement, the motor-pump, and an inverter with controller. Water resources are playing important role in human needs, such as agriculture, house hold purpose, for industrial applications, swimming pool/fountains, and for fire protection etc.

A number of machines have tested previously for PV power generation fed water pumping arrangement. The design of PV system based induction motor in agricultural applications as a water pump has been reported in [XIII, XI]. However, AC machines such as induction motor have many disadvantages like poor starting characteristics; overheating issues, less reliability and efficiency, and complex control. On the other hand, the DC machines are easy to control, but existence of commutator and brushes always need regular maintenance which is the major drawback with them. These limits forced the researchers to investigate for various other feasible options. Some researchers have concentrated on permanent magnet machines like brush-less DC (BLDC) driven PV based water pumping structure and permanent magnet synchronous motor (PMSM) driven PV based water pumping method reported in [XIV-XX]. These machines don’t require maintenance and operates with high efficiency. The main drawbacks of BLDC and PMSM are high cost because of permanent magnets (PM) and constant power operating region is low. Hence, the research interest has been shifted towards the reluctance machines.

A little research has been detailed with PV fed water pumping applications [XIX-XVI]. Reluctance machine is a kind of synchronous machine with a simple and cost effective construction. The stator part of the machine contains phase windings while the rotor is made up of steel laminations does not have any, it. Absence of windings and/or permanent magnets made the machine simple, cut-downs the machine weight, lessens the cost, and minimizes core losses and heat production [XIII]. SRM has the additional features like high speed, fast acceleration, unidirectional current, individual stator phase control, low inertia and high torque/inertia ratio [XII]. These features grab the attention on SRM from other machines. Although, torque ripple and noise are the major disadvantages of SRM. In the proposed model 8/6 SRM motor is considered because of more number of strokes in 8/6 pole configuration.

DC/DC converters are frequently used for many PV applications because of the merits like regulated output DC voltage. Various DC-DC converters have already proposed in the literature. ZETA converter has many advantages over the standard buck/boost type converters. Being a member of buck–boost converters family, the ZETA configuration can buck and/or boost the dc output. This feature also gives a large sector for maximum power-point (MPP) limits. Contrasting the traditional buck-boost converters, the ZETA configuration has the continuous output and ripples free current. Compared with a Cuk topology, the ZETA configuration produces non-inverting buck and/or boost output voltages [XVIII, II, XVII]. Also zeta converter does not require added circuitry for inrush current problem and does not need overload protection. These qualities made the ZETA converter favorable for PV based applications.
In this proposed arrangement, the zeta configuration is chosen to operate in continuous current conduction mode (CCM). This situation will allow reducing the switching stresses of the converter. A MPPT control strategy is used in the proposed system to produce the pulses which can control the zeta converter. There are a number of MPPT methods usually preferred for PV power generation to improve the efficiency. Among all these methods, a Perturbation and Observation technique is used in the proposed system because of its simplicity to implement, better performance with varying irradiance levels and accurate at MPP.

In this paper, an 8/6 SRM is used as a water pumping motor and is regulated by a 4-leg asymmetrical converter. Fig. 1 represents the ZETA fed SRM drive with PV system topology. MATLAB/simulink environment is used to design the proposed configuration. This system is also tested for different irradiance levels to verify its feasibility.

II. Proposed SRM Drive System

The schematic design of the proposed PV based ZETA converter has been presented to drive the SRM is illustrated in fig. 2. The ZETA configuration is used to regulate the variable dc generated by PV arrays. P&O MPPT scheme is developed for PV arrays to follow the maximum power. The design of P&O control algorithm is clearly explained in the next sections. The CCM operation of zeta converter reduces the component stresses, improves the efficiency and stabilizes the SRM drive structure. The detailed operation of ZETA converter is explained in the next section. Considering all the merits, an 8/6 SRM motor is preferred for the proposed system. To drive the SRM efficiently, a 4-leg asymmetrical converter is selected such that each phase winding of SRM motor is connected to each leg. The design procedure of proposed arrangement is enlightened in following sections.
III. Operation of ZETA Configuration

The ZETA configuration is a buck-boost type dc-dc regulator, provides tightly regulated non-inverted output voltage. In this section the operation of ZETA topology functioning in CCM is explained. From fig. 2 the ZETA converter consists of a dc-link capacitor (C_{dc}), inductors L_1 & L_2, an active switch (S), a coupling capacitor (C), and a free-wheeling diode (D_F). Fig. 3 shows the theoretical waveforms of ZETA converter in CCM when the switch S is ON and switch S is OFF. When the S is ON, dc-link capacitor C energized to V_{dc}, and is coupled in series with L_2; therefore the voltage across L_2 is +V_{PV}. The free-wheeling diode D_F voltage will be V_{PV} + V_{dc}. The energy from the input supply is being stored in L_1, L_2, and C.

When S is OFF, the voltage across L_2 must be V_{dc} since it is in parallel with C_{dc}. C_{dc} is charged to V_{dc} in steady-state; hence the voltage across S when it is OFF is given as V_{PV} + V_{dc}. The inductor values are designed to operate in CCM. This condition will reduce the switching stresses on the components. So the losses will be reduced which improves the efficiency of the converter. The currents flowing through various components are shown in fig. 3 under steady-state.
IV. Operation of SRM Drive

There are three operating modes in SRM motor drive system (see fig. 2) for each phase, namely excitation mode, freewheeling mode and demagnetization mode, which are revealed in Fig. 4. The following operation is explained for A–phase, which similar to all other phases. If the both active switches $S_1$ and $S_2$ are ON, the dc-link voltage $V_{dc}$ is directly appeared at phase-A winding, so the phase will get...
excited. This mode is called as excitation mode, as represented in Fig. 4 (a). If the switch $S_1$ is turned OFF and $S_2$ is ON, then the current will flow through diode $D_2$ as illustrated in Fig. 4 (b). This state is called as freewheeling mode. If both the switches $S_1$ and $S_2$ are turned OFF, the stored energy in the A-phase winding feedback to the input supply hence called as demagnetization mode as represented in Fig. 4 (c). In this mode, the current will flow through both diodes.

Figure 4: Operating modes of the asymmetrical topology for A – Phase. (a) Excitation mode. (b) Free-wheeling mode (ZVL). (c) Demagnetization mode.

V. Design Analysis of Proposed System

PV Array:

The PV array is a collection of various series & parallel PV panels generally include a lot of PV cells. Generally, earth’s environment has a solar irradiance level of 1000 W/m$^2$ including the entire losses in a peak time with sunny condition. The proposed PV array system is designed for 2.4kW (approximately) power rating significantly above than the SRM drives rating. This is with the assumptions of switching and conduction losses in the ZETA and asymmetrical configurations. The PV module ratings are open circuit voltage ($V_{oc}$) of 23.54 V, short circuit current ($I_{sc}$) of 5.01 A which are shown in table 1.

Table 1: Design elements of PV panel (Considering 90% efficiency, 25°C & 1000W/m$^2$)

| Element               | Value     |
|-----------------------|-----------|
| Max. Power ($P_m$)    | 2.5kW     |
| Open Circuit voltage ($V_{oc}$) | 23.54 V   |
| Voltage at MPP ($V_m$) | 22.48 V   |
| PV output Voltage ($V_{pv}$) | 179.85 V  |
| No. of series cells   | 8         |
| No. of parallel cells | 3         |
| Current at MPP($I_m$) | 4.51 A    |
| PV output Current ($I_{pv}$) | 13.53 A   |
Designing ZETA Configuration:

The zeta configuration provides regulated and variable DC voltage to the asymmetrical converter along with boundless area for achievement of MPPT method. The two inductors ($L_1$ & $L_2$) are calculated to operate in CCM, independent to irradiance levels. The ZETA converter parameters are calculated using design formula and are represented in table 2. The design procedure also requires the ripple estimation of $L_1$, $L_2$ currents (Considered 20%) and $C$, $C_{dc}$ (2%) voltages. The switching frequency $f_s$ of the configuration is selected as 10kHz.

| Table –2: Design elements of ZETA configuration |
|-----------------|-----------------|-----------------|-----------------|
| Element          | Formula                      | Calculated Value | Simulated Value |
| Duty Ratio D     | $V_{dc}/(V_{PV}+V_{dc})$    | 0.527            | 0.527           |
| Inductor $L_1$   | $V_{PV}D/dL_1f_s$           | 3.51mH           | 3.42mH          |
| Inductor $L_2$   | $V_{dc}(1-D)/dL_2f_s$       | 4.3mH            | 4.2mH           |
| Capacitor $C$    | $L_1(1-D)/dCf_s$            | 84μF             | 79μF            |
| Capacitor $C_{dc}$| $I_{dc}(30-\alpha)/2NP*dV_{dc}$ | 2.3mF            | 2.2mF           |

$N$ - Speed of SRM, $P$ – No. of Poles, $\alpha$ - Conduction angle.

P&O control scheme:

The P&O control scheme is mostly used MPPT among all other because of the merits like simple design, superior efficiency, and good performance under majority of operating circumstances. But, the main problem is, poor response to step change of solar radiation. P&O algorithm observes the variation in the power ($P_{PV}$) using $V_{PV}$ and $I_{PV}$ variables under the perturbation until the MPP is reached. Generally, mostly used perturbation variable is the voltage, but in this paper current ($I_{ref}$) is used because of the constant output voltage. If $P_{PV}$ increases, the direction of the perturbation will be same for the next step. If the power decreases, the direction will be revered. This procedure will remain same for every condition, weather there is any change in irradiation and or temperature. The ZETA converter switching pulse is generated using MPPT control algorithm and a ramp single with a fixed frequency of 10 kHz.

VI. Results

The effectiveness of ZETA fed SRM drive with PV system is demonstrated by simulation with two different conditions.

1) Variable Irradiance; and 2) Variable Speed
The simulation waveforms of two inductor currents namely $i_{L1}$ and $i_{L2}$, switch current ($i_{S}$) and PV currents ($i_{PV}$) of ZETA configuration have given in Fig. 5. As the ZETA converter is operating in complete CCM, so both the inductor currents are continuous as seen in the Fig. 5. It can be observed that the simulated waveforms confirm the theoretical analysis given in the previous sections. Fig. 6 demonstrates the voltage profile waveforms of ZETA converter in steady-state conditions.

![Figure 5: Simulated current waveforms of ZETA converter in steady-state. (a) $L_1$ Inductor Current (b) $L_2$ Inductor Current (c) Switch current and (d) Solar PV current](image)

![Figure 6: Simulated voltage waveforms of ZETA converter in steady-state (a) Solar PV voltage (b) AC coupling capacitor voltage and (c) Output voltage of ZETA converter.](image)

The Figure 7: represents the simulation response of the proposed configuration at constant isolation level and constant speed. Fig. 7 (a) represents the four phase flux linkages of SRM machine and its zoomed version at the starting and steady-state situation. The four phase SRM currents and its zoomed waveforms are illustrated in 7 (b) under starting and steady-state circumstances. Figure 7 (c) represents the estimated speed, reference speed and actual speeds of SRM machine (rated speed of 1500rpm). The Torque waveform and its zoomed version are shown in Figure 7 (d) under starting and steady-state conditions.
Figure 7: (a) Flux linkages of SRM drive for the four phases

Figure 7 (b) Phase currents of SRM drive for the four phases

Figure 7 (c) Speed waveforms of SRM drive under starting and steady-state conditions
Figure 7 (d) Torque waveform of SRM drive under starting and steady-state condition

**Variable Irradiance:**

Figure 8 represents the Step change in irradiance from 800 W/m² to 1000 W/m².

Figure 8 Step change of irradiance from 800 W/m² to 1000 W/m²

Fig. 9 corresponds to the performance curves of solar PV elements voltage $V_{PV}$, current $i_{PV}$ and power $P_{PV}$ for 800 W/m² & 1000 W/m² irradiance at starting and condition. All these curves are plotted at their rated values and current $i_{PV}$ is at preferred MPP value.
Figure 9 Performance curves of solar PV system at 800 W/m$^2$ and 1000 W/m$^2$ irradiances

The four phases of SRM currents and estimated, actual and reference speed waveforms are illustrated in Fig. 10 with a step change of irradiance from 800 W/m$^2$ to 1000 W/m$^2$. Figure 11 shows the four phase flux linkages and torque of SRM machine with a step change of irradiance 800 W/m$^2$ to 1000 W/m$^2$. As can be noticed that the flux and torque waveforms are constant and the torque ripple is also under control at steady-state conditions.

Figure 10 SRM four phase currents and speed waveforms with a step change of irradiance from 800 W/m$^2$ to 1000 W/m$^2$
Variable Speed:

Figure 12 shows the four phases of SRM currents and estimated, actual and reference speed waveforms with a step change in speed from 1000 rpm to 1500 rpm. The four phase flux linkages and torque waveforms of SRM machine is represented in Fig. 13 with a step change in the speed from 1000 rpm to 1500 rpm. It can be clearly observed that the actual speed is very close to the reference and estimated speeds under steady-state condition.
The above simulation cases have clearly shown the efficient regulation of speed of the SRM machine drive. The simulated P-V characteristics and I-V characteristics of solar PV system at 1000 W/m$^2$, 800 W/m$^2$ and 600 W/m$^2$ insolation levels are demonstrated in Fig. 14 (a-c). It can be seen that these characteristics represents the better MPPT performances.

VII. Conclusion

The design of Photovoltaic (PV) based ZETA converter has been presented in this paper, to drive the switched reluctance motor (SRM) for agricultural water pumping applications. A Perturbation and Observation (P&O) based MPPT algorithm is used to extract better power from the PV system. A dc-dc ZETA is linked in between PV and SRM drive as a front-end converter to provide steady and continuous dc input to the SRM drive for stable operation. In addition, the ZETA converter has
the advantage that it does not require additional circuitry for inrush current problem and does not need overload protection. The proposed system is developed using MATLAB/SIMULINK software to show its effectiveness. The variable DC link capacitor voltage of ZETA converter stabilizes the speed of SRM drive from variable environmental conditions and/or variable irradiation levels. The ZETA converter is operated in CCM which is also shown by the simulation inductor current waveforms. The simulation results has shown that the soft starting of SRM drive and minimizing the inrush starting current problem. Additionally, these simulation results have also show that the performance of the SRM drive system is improved at higher irradiance levels.

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