CHAPTER 1

INTRODUCTION

1.1 ENERGY AND WATER USE IN INDIA

Despite the focus on industrialization, agriculture remains the dominant sector of the Indian economy, both in terms of contribution to the gross domestic product (GDP) as well as the source of employment for millions across the country. Over 70% of the rural households depend on agriculture as their principal means of livelihood.

Renewable energy sources are beginning to play more of a role in urban areas such as building integrated photovoltaics, as well as in rural areas where wind, solar, biomass, and geothermal are gaining in popularity. When it comes to replacing the mass energy production of fossil fuels, renewable energy has not yet proven to be practical. However, renewable energy sources do excel in local applications where there is limited or no access to an electricity grid, or where access to conventional energy is prohibitively expensive. They are most efficient in local applications because the energy production is at the same location as the end-use, hence minimizing the need for energy storage and transport. Of the energy consumers within agriculture, the timing of irrigation requirements conveniently coincides with an increase in insolation/intensity of solar radiation, creating great potential for the union of irrigation and solar energy, specifically photovoltaic systems (Raghav et al 2013).
The statistics in Tables 1.1 to 1.3 show the data on wells, tube wells, diesel and electric pumps from four sources, namely, Minor Irrigation Census (MIC), Agricultural Census (AgC), Input Survey (InS) and statistics from State Electricity Boards (SEBs) and/or the State Statistical Bureaus (Rawat & Mukherji 2012). Table 1.1 gives the number of wells and tube wells for select states in India; Table 1.2 gives the number of diesel pumps for select states in India; and Table 1.3 gives the number of electric pumps for select states in India.

Table 1.1  Number of wells and tube wells for select states in India (in Lakhs)

<table>
<thead>
<tr>
<th>Year &amp; census</th>
<th>State</th>
<th>Tamil Nadu</th>
<th>Kerala</th>
<th>Andhra Pradesh</th>
<th>Karnataka</th>
<th>Total (in India)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid 1980s</td>
<td>AgC I (1985-86)</td>
<td>2.74</td>
<td>27.91</td>
<td>8.53</td>
<td>3.85</td>
<td>121.61</td>
</tr>
<tr>
<td></td>
<td>MIC I (1986-87)</td>
<td>15.93</td>
<td>1.24</td>
<td>12.99</td>
<td>4.53</td>
<td>114.64</td>
</tr>
<tr>
<td>Mid 1990s</td>
<td>AgC II (1995-96)</td>
<td>5.80</td>
<td>37.58</td>
<td>14.45</td>
<td>8.53</td>
<td>173.17</td>
</tr>
<tr>
<td></td>
<td>MIC II (1993-94)</td>
<td>14.19</td>
<td>1.29</td>
<td>15.65</td>
<td>5.52</td>
<td>116.23</td>
</tr>
<tr>
<td>Early 2000s</td>
<td>AgC III (2000-01)</td>
<td>19.38</td>
<td>43.80</td>
<td>17.76</td>
<td>8.59</td>
<td>188.45</td>
</tr>
<tr>
<td></td>
<td>MIC III (2000-01)</td>
<td>18.92</td>
<td>1.71</td>
<td>19.29</td>
<td>8.60</td>
<td>185.03</td>
</tr>
<tr>
<td>Mid 2000s</td>
<td>AgC IV (2005-06)</td>
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<td>47.19</td>
<td>18.22</td>
<td>8.21</td>
<td>184.90</td>
</tr>
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<td></td>
<td>MIC IV (2006-07)</td>
<td>18.66</td>
<td>1.70</td>
<td>22.00</td>
<td>9.78</td>
<td>197.56</td>
</tr>
</tbody>
</table>

Courtesy: Water Policy Research Highlight-5, 2012
Figure 1.1 represents the number of wells and tube wells in India taken from MIC, AgC, InS and SEBs (Rohit et al 2013).

Figure 1.1 Number of wells and tube wells in India (in lakhs)

Table 1.2 Number of diesel pumps for select states in India (in lakhs)

<table>
<thead>
<tr>
<th>Time period</th>
<th>States</th>
<th>Tamil Nadu</th>
<th>Kerala</th>
<th>Andhra Pradesh</th>
<th>Karnataka</th>
<th>Total (In India)</th>
</tr>
</thead>
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<tr>
<td>1986-87</td>
<td>AgC (1985-86)</td>
<td>0.38</td>
<td>0.42</td>
<td>1.76</td>
<td>0.14</td>
<td>32.41</td>
</tr>
<tr>
<td></td>
<td>InS (1986-87)</td>
<td>3.86</td>
<td>0.37</td>
<td>1.55</td>
<td>0.77</td>
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<tr>
<td></td>
<td>MIC (1986-87)</td>
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<td>2.15</td>
<td>0.43</td>
<td>35.11</td>
</tr>
<tr>
<td>1993-94</td>
<td>AgC (1995-96)</td>
<td>1.01</td>
<td>0.31</td>
<td>1.09</td>
<td>0.61</td>
<td>47.14</td>
</tr>
<tr>
<td></td>
<td>InS (1991-92)</td>
<td>3.77</td>
<td>1.19</td>
<td>3.1</td>
<td>1.19</td>
<td>68.92</td>
</tr>
<tr>
<td></td>
<td>MIC (1993-94)</td>
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<td>0.15</td>
<td>1.49</td>
<td>NA</td>
<td>41.7</td>
</tr>
<tr>
<td>2000-01</td>
<td>AgC (2000-01)</td>
<td>1.35</td>
<td>0.51</td>
<td>0.41</td>
<td>0.11</td>
<td>42.16</td>
</tr>
<tr>
<td></td>
<td>InS (2001-02)</td>
<td>12.39</td>
<td>0.68</td>
<td>5.31</td>
<td>1.51</td>
<td>142.61</td>
</tr>
<tr>
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<td>MIC (2000-01)</td>
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<td>0.1</td>
<td>1.18</td>
<td>0.3</td>
<td>63.39</td>
</tr>
<tr>
<td>2005-06</td>
<td>AgC (2005-06)</td>
<td>4.71</td>
<td>0.23</td>
<td>0.44</td>
<td>0.42</td>
<td>45.37</td>
</tr>
<tr>
<td></td>
<td>InS (2006-07)</td>
<td>5.59</td>
<td>0.35</td>
<td>4.9</td>
<td>2.5</td>
<td>131.8</td>
</tr>
</tbody>
</table>

Courtesy: Water Policy Research Highlight-5, 2012
Table 1.3 Number of electric pumps for select states in India (in lakhs)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>State</th>
<th>Tamil Nadu</th>
<th>Kerala</th>
<th>Andhra Pradesh</th>
<th>Karnataka</th>
<th>Total (in India)</th>
</tr>
</thead>
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<tr>
<td>1986-87</td>
<td>AgC (1985-86)</td>
<td>1.69</td>
<td>2.17</td>
<td>4.75</td>
<td>3.42</td>
<td>38.2</td>
</tr>
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<td></td>
<td>InS (1986-87)</td>
<td>12.18</td>
<td>1.6</td>
<td>3.79</td>
<td>2.91</td>
<td>63.49</td>
</tr>
<tr>
<td></td>
<td>MIC (1986-87)</td>
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<td>NA</td>
<td>7.38</td>
<td>3.5</td>
<td>46.85</td>
</tr>
<tr>
<td></td>
<td>SEB</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1993-94</td>
<td>AgC (1995-96)</td>
<td>4.18</td>
<td>6.32</td>
<td>12.71</td>
<td>7.08</td>
<td>80.44</td>
</tr>
<tr>
<td></td>
<td>InS (1991-92)</td>
<td>9.66</td>
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<td>13.4</td>
<td>7.9</td>
<td>93.24</td>
</tr>
<tr>
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<td>MIC (1993-94)</td>
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<td>13.08</td>
<td>NA</td>
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<td>2000-01</td>
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<td>13.08</td>
<td>7.96</td>
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</tr>
<tr>
<td></td>
<td>InS (2001-02)</td>
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<td>7.86</td>
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<td>NA</td>
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<tr>
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<td>17.2</td>
<td>7.35</td>
<td>101.72</td>
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<tr>
<td></td>
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<td>27.88</td>
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<td>127.14</td>
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<td></td>
<td>SEB</td>
<td>18.02</td>
<td>NA</td>
<td>24.41</td>
<td>17.14</td>
<td>NA</td>
</tr>
</tbody>
</table>

Courtesy: Water Policy Research Highlight-5, 2012

1.2 SOLAR PHOTOVOLTAIC (SPV) SYSTEM

The photovoltaic (PV) system uses the sun’s energy to generate power for domestic or industrial appliances that require the use of conventional electricity. This technology directly converts sunlight into electricity using semiconductor cells, called PV cells.
1.2.1 **Standard Test Conditions of the SPV**

The electrical output of the PV panel is rated according to industry the Standard Test Conditions (STC) of 1000 W/m² incident solar radiation at an operating cell temperature of 25 °C and under an absolute air mass of 1.5. Figure 1.2 shows the irradiance level in Chennai. The insolation incident on the solar panels is maximized by orienting the module relative to the sun. This is because the reflection of the direct beam component of the solar radiation, off the panel surface, greatly increases when the angle of incidence, the angle between the beam incident on the surface and a line perpendicular to the surface, is greater than 60°.

Tracking panels that follow the movement of the sun decrease the angle of incidence, and therefore increase the amount of available solar radiation. If the tracking is not available, a good year round compromise is to mount the panels at an angle from the horizontal that is equal to the site latitude, facing solar South (when panels are located in the Northern Hemisphere). Otherwise, the optimal tilt angle varies with the seasons depending on the declination or the angular position of the sun at solar noon.

The effect of irradiance levels on the performance of the solar array is governed by the module technology. Each module is defined by its rated parameters. One such parameter is the maximum power voltage, $V_{mp}$, which indicates the modules behaviour or performance in low light conditions. This is an important variable to consider, when the solar array is situated in a typical cloudy location, where the levels of irradiance will be less than the STC. The operating cell temperature, which is governed by the panel mount, insolation, ambient temperature, as well as the wind speed and direction, also play an important role in module performance.
A number of PV cells are connected in series to form a PV module to get the useable voltage. Conventionally, 36/72 cells are connected in series to form a typical PV module. The PV modules are then connected in parallel, thereby increasing the voltage and current rating of the array, to meet the load demand. The electrical power generated by the PV arrays must be controlled and sometimes modified to meet the electrical demand. The output from the available commercial PV modules is unregulated DC. Output from the PV array may vary, with respect to environmental parameters.

To regulate/modify the PV array output, power controllers such as maximum power point trackers (MPPT) are used (Arora & Sharma 2014). The MPPT maintains the operating voltage of the array at a specific value that maximizes the array output. This output can feed DC load. If the load is AC such as AC motors, utility grid, etc., inverters are used (Hua & Shen 1998).

1.3 SOLAR PHOTOVOLTAIC APPLICATIONS

The use of PV technology varies considerably, from PV cells in calculators and watches, to PV modules in telecommunications equipment.
and highway signs, to PV arrays for water pumping and generating electricity in agricultural and rural areas (Kabade 2013).

An important aspect of the PV system is the energy storage capacity. A method of storing energy is to use the solar power to pump water to a higher elevation, thus transferring the electrical energy to potential energy (Dursun & Ozden 2012). Water pumps used depend greatly on the type of application (Sodiki 2014). Positive displacement pumps offer low volume with high lift capabilities, whereas rotating pumps are best for large water requirements over any lift. Floating and surface suction pumps offer a range of volumes at low lift only. Submersible pumps are the most efficient for use in a PV pumping system, as they eliminate the suction line.

Another factor to consider in the selection of the pump is the type of motor. The motor can be DC or AC and the decision should be based on the price, reliability, and the technical support that is available. Permanent magnet DC motors can connect directly to the PV array. They are reliable, efficient, and operate over a wide range of voltages. For the agricultural use, mostly AC motors are used to pump water from the wells or deep bores. Single-phase induction motors and three-phase induction motors are widely used for agriculture water pumping. AC motors require the use of an inverter, but are less expensive and more readily available (Babu & Rao 2014).

Another application where solar energy is used is in the area of battery charging. These applications require electrical energy on demand so that the solar panels are used to charge batteries (during sunlight hours). In turn, these batteries provide electricity when required during the night. Deep-cycle batteries are most appropriate for PV application as they can withstand cycles of up to 80% discharge. There are many concerns like maintenance, frequent replacement, etc., while using battery storage. This in
turn increases the cost of the system. The best way to use the PV system is to use it without battery storage.

1.3.1 Solar Photovoltaic Water Pumping System (SPVWPS)

The water pumping system with PV is most commonly used as a complete PV system, both in developed and developing areas (NSW Farmers 2015). Water pumping applications include, but are not limited to, domestic water, irrigation, livestock watering, and village water supplies (Jenkins 2014). In combining irrigation and solar energy, a small PV system can be used to power a water pump for small-scale irrigation (Maurya 2015). Figures 1.3 and 1.4 show the block diagrams of the Solar Photovoltaic DC water pumping system (SPV DC WPS) and Solar Photovoltaic AC water pumping system (SPV AC WPS).

Figure 1.3 Block diagram of solar photovoltaic DC water pumping system

Figure 1.4 Block diagram of solar photovoltaic AC water pumping system
PV water pumping for agriculture and irrigation is especially prevalent as there is a correspondence between the water requirements of plants and the availability of the solar energy. There are many advantages of using a PV system for generating power for water pumping. The location of the system is very flexible in that it can be completely off-grid or grid-tied. In off-grid applications, PV systems are the most competitive against the alternatives, namely, the extension of a utility grid, disposable batteries, and generators of all types (diesel, gasoline or thermoelectric) (Khlifi 2015).

The most efficient use of the solar energy is to connect the load directly to the PV system (Elgendy et al 2010). In fact, the success of the water pumping system lies partly in eliminating the intermediate phase of energy storage in terms of battery. With a direct connection between the PV array and the pump, water can be pumped during the sunlight hours.

The most efficient form of direct-connect systems is the water pumping system. The water is pumped to an elevated storage tank, thus the electrical energy from the PV system is converted to potential energy of the elevated water. The stored water can be used on demand, often by gravity. The overall efficiency, from sunlight to water flow, has been recorded to exceed 3% as compared to the direct pumping system.

The overall efficiency of water pumping system (WPS) setup varies and depends on factors like the environment, controllers, type of motor and any additional components. The typical life span of a solar panel is 25 years and though the initial investment can be quite large, the payback period is usually within 5 to 10 years, depending on the size of the system. In addition, the PV water pumping system is also easy to install and maintain (Oi 2005).
1.4 INFERENCES

As the cost of the fossil fuel continues to rise and the environmental effects of fossil fuel power become ever more apparent, discovering alternative energy sources becomes increasingly important. The PV technology is continually improving, becoming more efficient over a range of environmental conditions, while at the same time decreasing in cost. The PV water pumping system is commonly used in many countries and this system can only improve in efficiency and effectiveness in the coming years.

With an increasing understanding of the solar radiation and the associated PV electrical output, new models that are more accurate are being developed. The union of PV and irrigation could be a positive step toward sustainable agriculture. With this in mind, it was apparent that more research needed to be carried out in the field of PV and its use in pumping water, both for practical and modeling purposes. The amount of water pumped is dependent on the amount of PV energy available, which is governed by the amount of solar radiation reaching the earth’s surface at a given site.

Therefore, the focus of this research is to concentrate on the SPV fed water-pumping system (SPVWPS) using the existing AC motors and testing the feasibility of other types of AC motors that can be more cost effective.

1.5 RESEARCH MOTIVATION

The literature study revealed that dependency on grid power supply required for meeting the energy demand - a basic need for growth and development of rural India. This can be reduced using the SPV system. The supplementary or alternative sources of SPV could result in a green environment by providing electricity and water for drinking and irrigation in
every rural home resulting in increasing agricultural productivity, economic status, and standard of living etc. (Pullenkav 2013).

Further, the impact of the system on rural masses in different spheres of life has been predicted and estimated as a percentage increase (on an average) as follows:

- Education - 50%
- Heath, hygiene and sanitation - 60%
- Income generation - 80%
- Quality of life - 40%

This technology could play a vital role in rural development and bring in a green revolution among the rural masses.

1.6 RESEARCH OBJECTIVES AND CONTRIBUTION

The thesis presents the basis for choosing the SPV operated water pumping system with the best AC drive system for agriculture water pumping solution. The research objectives are:

- To understand the need for a water pumping systems using the SPV.
- To study the various types of SPVWPS and different types of pumps required for agriculture, irrigation, and domestic needs.
- To analyse financially and compare the SPVWPS and existing diesel operated WPS.
- To model the SPVWPS for operation with different AC motors subject to constant and variable irradiance levels.
To simulate and compare the performances of various drive systems to cater to the needs of water pumping solutions.

To implement a prototype system to meet the above requirements.

1.7 LITERATURE REVIEW

Literature review in the following areas is presented:

i. Modelling of the SPVWPS

ii. SPVWPS for irrigation and agriculture

iii. Economics and cost analysis of the SPVWPS

1.7.1 Modelling of Solar Photovoltaic Water Pumping System

Hosseini et al (2010) investigated the optimal operation performance of a BLDC fed by a Z-source inverter with an SPV system, which drives a water pumping system. The work was carried out in the MATLAB/Simulink simulation environment.

Feyzi et al (2011) developed a BLDC fed by a Hybrid Distributed Generation System (HDGS). The HDGS was accompanied with an SPV array, fuel cell stacks, and a battery to supply a fixed power for driving a BLDC motor in the MATLAB/Simulink simulation environment.

Chikuni (2012) presented a methodology for sizing and designing an SPV system based water-pumping system from the components available in South Africa. The work showed that the solar pumping technology has gone past the experimental and prototype stage.
Acakpovi et al (2012) investigated the SPVWPS deployed in remote areas for providing drinking water and irrigation (Singh et al 2010). Due to the high cost of solar energy implementation, the system becomes very costly. Unfortunately, inaccuracies in the system sizing mostly lead to oversizing, resulting in a huge waste of money. Therefore, the work focused on a mathematical method for sizing photovoltaic water pumping systems with more accuracy.

Hammadi et al (2013) developed a field oriented control (FOC) drive scheme for an isolated SPVWPS. The simulation of the PV system supplying a centrifugal PMSM coupled pump is carried out. The dynamic performance of the PV panel, the buck converter, and the motor were analyzed. Simulation results show that the proposed FOC methodology is an efficient solution.

Mohammedi et al (2013) describe the operation of the pumping system to supply drinking water. The developed prototype model was used to characterize the motor-pump subsystem used in PV pumping installations. The model expresses the water flow output (Q) directly as a function of the electrical power input (P) to the motor-pump, for different total heads. The prototype model was tested for operating pumping systems destined to supply drinking water. The performances were compared in terms of total height and geographical site of Bejaia (Algeria).

1.7.2 Solar Photovoltaic Water Pumping for Irrigation and Agriculture

Eker (2012) analyzed the application of WPS to cater to the needs of agriculture and found that SPV was the best solution for remote agricultural needs such as water pumping for crops or livestock (Doorenbos & Pruitt 1977). The work focused on the working of the SPVWPS and
considered the effective utilization of solar power that would lead to cost-competitive solution in comparison with traditional energy sources for small, remote applications.

Malla et al (2011) designed a standalone SPV for irrigation and drinking water. The work focused on improving the efficiency of the SPVWPS with perturb and observe (P&O) algorithm based MPPT and provide a cost-effective solution without the use of the battery system. The simulated results show that the performance of the controllers both in transient as well as in steady state was quite satisfactory.

Vick & Clark (2009) tested different types of SPVWPSs. The work showed several steps that are needed to select a SPVWPS and they analyzed the monthly water demand requirement. Three case studies were included to demonstrate the selection of PV array size, motor/pump rated power, and type of pump. The results of the work show that the standard 24 V multi-crystalline silicon PV modules were found to be a better choice than high voltage multi-crystalline or thin-film modules.

1.7.3 Economics and Cost Analysis of the System

Alireza & Asghar (2013) analyzed the technical and financial study on SPVWPS for irrigation of Gorgan’s farm fields (one of the Northern Provinces of Iran) with the RETScreen software tool. The results show that the use of solar energy reduces the production costs during its operation. The analysis inferred that implementation of SPVWPS has a low payback period.

Narale et al (2013) investigated the design and economic analysis of an efficient SPVWPS for irrigation of the banana crop. The system was designed and installed in the solar farm of Jain Irrigation System Limited (JISL) at Jalgaon, Maharashtra. The PV system was sized for irrigating
0.165 ha of banana plot having a daily water requirement of 9.72 m\(^3\)/day and total head of 26 m. In addition, the life cycle cost (LCC) analysis was conducted to assess the economic viability of the system. The installed system of SPVWPS was capable of irrigating 0.165 ha area of banana crop within 6.02 hrs for a daily water requirement of 9.72 m\(^3\)/day.

The results of the study indicate that irrigating orchards in the remotest areas using the PV systems are beneficial and suitable for long-term investments as compared to the diesel-powered engines. In addition, the LCC of the PV system was much lesser than that of the diesel engine.

1.8 ORGANISATION OF THE WORK

Figure 1.5 presents the organization of the research work.

1.8.1 Chapter 1 – Introduction

This chapter gives a brief introduction of the present scenario of the electricity demands and the need for alternative solutions for water pumping system that are used in agriculture. It gives a basic idea of the energy needs to meet the present conditions of power outages and the need for renewable energy systems to power the electricity in agriculture. The chapter gives the applications of SPV systems and extends it to cater to the needs of the water supply for agriculture. It gives an overall view of the various water pumping schemes available for pumping water in Tamilnadu, India. This chapter focuses on the SPV fed WPS with the existing AC motors and test the feasibility of other types of AC motors that can be cost-effective.
Figure 1.5 Roadmap of the research work
1.8.2 Chapter 2 – Design and Mathematical Modelling of Components of the Water Pumping System

This chapter presents the basic components needed for the SPV WPS. It focuses on the selection of the solar panels, sizing of the system, and the selection of the load to be connected based on the system requirement. The chapter also discusses the controllers used to deliver power from the intermediate system (MPPT controller) (Srushti et al 2015) and to the controller (SVPWM inverter), which operates the AC motor connected to the pump (Ram & Ramana 2014).

The chapter presents the description and selection of various AC motor drive systems to operate the pump. The performance index of the various pumps that are used as surface or submersible pumps for WPS are discussed. An idea about the various diesel engines that are used for WPS is also presented.

1.8.3 Chapter 3 - Financial Analysis of Solar PV Pumps

This chapter analyses in terms of economics of IM/BLDC SPVWPS and the diesel WPS. The cost analysis was performed considering the initial cost, operating cost, maintenance cost and replacement cost. The detailed results presented include the life cycle cost (LCC) for an average water pumping installation and for a 60 m of delivery head.

1.8.4 Chapter 4 - Simulation of the Solar Water Pumping System

This chapter gives the design and simulation of induction motor, permanent magnet synchronous motor and Brushless DC motor operated SPVWPS. The three systems are made to operate in open-loop control to deliver water under constant and variable irradiance levels. The analysis of
the systems for constant and variable irradiance levels was done and the performances of the systems are compared.

### 1.8.5 Chapter 5 - Simulation of Closed Loop Control of Solar Water Pumping System

This chapter gives the design and simulation of three different SPVWPS with closed loop control to deliver a constant throughput even when the irradiance level changes. In order to use the existing induction motors for agriculture use, simulation of the SPV fed induction motor water pumping system was analyzed at standard operating conditions of 1000 W/m² at 25 °C. In addition, the induction motor drive system was subjected to worst change of irradiance level varying from 200 W/m² to 1000 W/m².

The effect of the changes in the irradiance level and the corresponding response of the induction motor drive systems are analyzed. The same irradiance effects are applied to the permanent magnet BLDC and permanent magnet synchronous motor (PMSM) drive systems to deliver a constant throughput. The simulations are analyzed and the performances of these systems were compared based on response and adaptability to the change in the irradiance level.

### 1.8.6 Chapter 6 - Hardware Implementation of the Prototype BLDC Solar Water Pumping System

This chapter gives the development of the prototype and testing of the SPV fed BLDC WPS. The system was subjected to the constant irradiance level and the results were analyzed. The prototype system was also tested for change in the irradiance level and corresponding analysis was performed. The hardware results were compared with the simulation results.
1.8.7 Chapter 7 – Conclusion

This chapter gives the conclusions of the work presented in this thesis and the scope for future use.