CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

The growth of the Motor and the Pump Industry started during the early 1920’s and has been quite commendable since then. The first Submersible pump was developed in the year 1928 in India at Coimbatore. The PSG Industrial Institute and Dhandayudhapani foundry of Coimbatore were the pioneers in the field of pump manufacturing and the first motor was released at Argus in 1937. The stimulus for growth came mainly from the emphasis on development of agriculture sector and the strengthening of the industrial sector during the successive five year plans. Subsequent to the first five year plan period, a lot of emphasis was placed on agriculture and rural electrification, which led to a tremendous growth in the Pump Industry. The 70’s can be considered as the golden era as far as the Pump Industry is concerned, and particularly for Coimbatore. From 1991 to 1996, the growth of the Pump Industry was driven mostly by the boom in industries and urbanization due to the liberalization policy.

The Indian Pump Industry is poised to register a faster growth rate than the global average. The industry is set to grow at approximately 4.4 % of the global market share in 2015, from 2.9 % in 2005 (i.e., US$ 1.25 billion in 2015 vis-á-vis US$ 0.625 billion in 2005). According to Industry estimates, India produces 1.2 million pumps of various kinds. There are around 800 large, medium, and small units producing pumps for sectors ranging from
Agriculture to Nuclear Power. Indian Pump Manufacturers are able to meet most of the domestic market demand. Exports have registered a 11% growth in the last two years. India has today become a reliable, technically competent, competitive, and enterprising outsourcing option for many western pump manufacturers, who will continue to buy more low-cost pump parts, or sell 'private-label' complimentary pumps of other manufacturers, instead of manufacturing their own.

The turnout of Indian Pumps and Motor Industry is of the order of Rs.3500 Crores which makes it to be about 2.5% of the world market. Indian Pumps and Motors are now being exported to more than 70 countries, both developed and developing countries. This can be expected to increase further, and exported across many more countries around the world through proper interventions.

The organized pump motor manufacturers are mostly members of Southern India Engineering Manufacturers Association (SIEMA) and Coimbatore District Small Scale Industries Association (CODISSIA), while majority of the members in Tamilnadu Pump and Industrial Manufacturers Association (TAPMA) represent unorganized group of manufacturers; there exists strong linkages with these Building Measures of the Associations (BMOs), SIEMA and CODISSIA are creating awareness on the need to produce Energy Efficient Pump Motors and the benefits of certification to unorganized pump manufacturers.

2.2 ENERGY SCENARIO IN AGRICULTURE

Submersible Induction Motors account for approximately 35% of the overall electricity use in countries like India. On an average, the energy consumed by a motor during its life cycle is 60-100 times the initial cost of the motor. The Tamil Nadu Electricity Board is a corporate body constituted under the Electricity (Supply) Act, 1948 (Central Act 54 of 1948) and
authorized to function as “The State Transmission Utility and a Licensee” under the Notification issued by the Government of Tamil Nadu under clause (a) of Section 172 of the Electricity Act, 2003. The main objectives of Tamil Nadu Electricity Board are to generate, transmit, and distribute electricity efficiently, and to ensure supply of quality power to its consumers. As on 31.03.2010, the growth of consumers and the growth pattern of consumers are shown in Table 2.1 and in Figure 2.1, respectively.

Table 2.1 Growth of Consumers during 2005-2010

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>119.74</td>
<td>125.28</td>
<td>130.64</td>
<td>136.64</td>
<td>141.42</td>
</tr>
<tr>
<td>Agriculture</td>
<td>17.68</td>
<td>18.02</td>
<td>18.39</td>
<td>18.73</td>
<td>19.12</td>
</tr>
<tr>
<td>Commercial</td>
<td>21.23</td>
<td>22.27</td>
<td>23.43</td>
<td>24.97</td>
<td>26.32</td>
</tr>
<tr>
<td>Industrial</td>
<td>4.36</td>
<td>4.51</td>
<td>4.71</td>
<td>4.89</td>
<td>5.10</td>
</tr>
<tr>
<td>Others</td>
<td>15.02</td>
<td>15.74</td>
<td>17.16</td>
<td>18.65</td>
<td>20.09</td>
</tr>
<tr>
<td>Total</td>
<td>178.03</td>
<td>185.82</td>
<td>194.33</td>
<td>203.88</td>
<td>212.05</td>
</tr>
</tbody>
</table>

Source: The Chief Engineer Planning, Tamil Nadu Electricity Board, Chennai-2

Figure 2.1 The Growth Pattern of Consumers from 2005 to 2010
The consumption of energy during 2009-2010 in Tamilnadu is shown in Figure 2.2.

![Figure 2.2 Percentage of Energy Consumption during 2009-2010](image)

A significant amount of energy consumed by the Agriculture sector is provided as free by Tamilnadu Government to the farmers. In addition to Agriculture, Open-well Pump for pumping water from sump to over-head in all residential and commercial complexes comes under domestic sector. Similarly, Motor Pumps consume considerable energy in Public Water Distribution.

The number of Agriculture pump-sets energized during the year 2009-2010 in Tamilnadu is shown in Table 2.2.
Table 2.2  Agriculture Pump-sets energized during the year 2009-2010 in Tamilnadu

<table>
<thead>
<tr>
<th>Electricity Distribution Circle</th>
<th>No. of Pump-sets energized in 2009-10</th>
<th>Pump-sets Energized as on 31.3.2010</th>
<th>Electricity Distribution Circle</th>
<th>No. of Pump-sets energized in 2009-10</th>
<th>Pump-sets Energized as on 31.3.2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coimbatore</td>
<td>3125</td>
<td>124348</td>
<td>Salem</td>
<td>1775</td>
<td>119531</td>
</tr>
<tr>
<td>Cuddalore</td>
<td>1035</td>
<td>67602</td>
<td>Sivagangai</td>
<td>600</td>
<td>22279</td>
</tr>
<tr>
<td>Dharmapuri</td>
<td>1753</td>
<td>105313</td>
<td>Thanjavur</td>
<td>641</td>
<td>58069</td>
</tr>
<tr>
<td>Kancheepuram</td>
<td>1676</td>
<td>71557</td>
<td>Theni</td>
<td>589</td>
<td>35169</td>
</tr>
<tr>
<td>Dindigul</td>
<td>1666</td>
<td>89296</td>
<td>Tirunelveli</td>
<td>1615</td>
<td>76869</td>
</tr>
<tr>
<td>Erode</td>
<td>1039</td>
<td>131007</td>
<td>Tiruvurur</td>
<td>0</td>
<td>20622</td>
</tr>
<tr>
<td>Kanyakumari</td>
<td>180</td>
<td>7177</td>
<td>Tiruvannamalai</td>
<td>2292</td>
<td>166472</td>
</tr>
<tr>
<td>Krishnagiri</td>
<td>0</td>
<td>6859</td>
<td>Tiruvallur</td>
<td>0</td>
<td>45989</td>
</tr>
<tr>
<td>Madurai</td>
<td>682</td>
<td>49316</td>
<td>Trichy</td>
<td>2032</td>
<td>82657</td>
</tr>
<tr>
<td>Nagapattinam</td>
<td>399</td>
<td>25507</td>
<td>Tuticorin</td>
<td>299</td>
<td>29372</td>
</tr>
<tr>
<td>Namakkal</td>
<td>790</td>
<td>78007</td>
<td>Vellore</td>
<td>1797</td>
<td>131585</td>
</tr>
<tr>
<td>Nilgiris</td>
<td>24</td>
<td>1245</td>
<td>Villupuram</td>
<td>2526</td>
<td>164490</td>
</tr>
<tr>
<td>Pudukkottai</td>
<td>1021</td>
<td>52110</td>
<td>Virudhunagar</td>
<td>416</td>
<td>36630</td>
</tr>
<tr>
<td>Perambalur</td>
<td>0</td>
<td>50410</td>
<td>Ariyalur</td>
<td>0</td>
<td>530</td>
</tr>
<tr>
<td>Ramanathapuram</td>
<td>99</td>
<td>8288</td>
<td>TOTAL</td>
<td>28071</td>
<td>1858306</td>
</tr>
</tbody>
</table>

Source: The Chief Engineer Planning, Tamil Nadu Electricity Board, Chennai-2

From Table 2.2, it is clear that there is considerable increase in consumers and energy consumption in the Agriculture sector. Agriculture sector consumes about 21% of the total power generated. Most of the farmers use inefficient non-standard pump-sets which consume more electricity and deliver less output. There is a potential of about 25 to 35% improvement in the efficiency of these pump-sets by effecting minor/major rectification and shifting to ISI-marked standard pumps. BEE has unveiled improved energy efficiency norms for the Electric Motor and Pump Industry. These norms may put energy efficiency standards higher than the Bureau of Indian Standards.
(BIS) norms for the pump industry. The motors manufactured by unorganized
units do not have ISI standards and is less efficient due to non-use of higher
quality material resulting in iron-loss and copper loss. The no-load power
factor is above 0.2, which in essence increases the no-load power
consumption. There exists a mismatch in supply of pumps and motors by the
unorganized sector as per operating load required by the client. Scope for
energy conservation in agricultural pumping is vast, as nearly 50% of the
connected load on the National grid comprises of Agricultural Pumps.
Meaningful results in this sector can be achieved only by providing adequate
checks and balances. Self-certification will result in many unorganized
manufacturers like KIT assemblers to declare wrongly their product as five
star rated products, even though they do not meet the parameters of five stars.
This will keep the quality-conscious and organized manufacturers away from
the whole process, as these KIT sectors can offer such bogus five star
products at a price much cheaper than the quality-branded products, as they
do not pay any Excise Duty, Sales Tax etc. A check on this will really
encourage quality manufacturers to enroll themselves in the scheme. Major
portion of the connected load on the National grid is for agricultural pumps;
but, unfortunately the farmers have no motivation to conserve energy, while
buyers of refrigerators or air conditioners would themselves be concerned
very much for the energy bills to be paid for. So, it is essential that BEE
should insist for a certificate from NABL-approved labs for the products
registered for star ratings. The star rating plan for pump-set specifies the
requirements for participating in the energy labeling scheme for pump-sets
covering Electric mono set pumps, submersible-pump-sets, and open-well
submersible-pump-sets. The standard ratings covered under the energy
labeling scheme are as shown in Table 2.3.
Table 2.3 Standard Ratings covered under the Energy Labeling Scheme

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Product detail</th>
<th>Product Range in kW</th>
<th>No. of Poles</th>
<th>Applicable IS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3-Phase open-well submersible-pump-sets</td>
<td>0.37, 0.55, 0.75, 1.1, 1.5, 2.2, 3.7, 5.5, 7.5, 9.3, 11, and 15</td>
<td>2</td>
<td>IS 14220 : 1994</td>
</tr>
<tr>
<td>2</td>
<td>3-Phase Submersible-pump-sets</td>
<td>1.1, 1.5, 2.2, 3.0, 3.7, 4.5, 5.5, 7.5, 9.3, and 11</td>
<td>2</td>
<td>IS 8034 : 2002</td>
</tr>
<tr>
<td>3</td>
<td>3-Phase Mono-set-pumps</td>
<td>0.37, 0.55, 0.75, 1.1, 1.5, 2.2, 3.7, 5.5, 7.5, 9.3, 11, and 15</td>
<td>2</td>
<td>IS 9079 : 2002</td>
</tr>
</tbody>
</table>

Therefore, efficiency of the motor is of paramount importance both during selection and operation. A good magnetic circuit design of submersible Induction Motor with low production cost, efficient utilization of existing submersible Induction Motor with miniaturized low cost electronic circuit that is integrated with starter, and other motors like Switched Reluctance Motor, which have a suitable speed-torque characteristic for submersible centrifugal pump can achieve a reduction in overall energy losses and a consequent increase in energy efficiency.

The next section reviews the various techniques used so far for improving the efficiency of Induction motors and submersible Induction Motors, the application of submersible motors with controllers and their needs, and design constraints of Switched reluctance motors for different applications.
2.3 REVIEW OF ENERGY-EFFICIENT INDUCTION MOTOR AND ITS DESIGN

The electric motor has a long history of development since its invention by Nicola Tesla in 1888, with continuous effort aimed at improving power and torque at reduced cost (Haque 2008). The need for higher efficiency became apparent during the late 1970’s and by the early 1980’s. At last, one British manufacturer started to market a premium range of motors with improved efficiency. Now the trend is towards the design and manufacturing of motors with a small improved efficiency at a small extra cost. It is needless to state that, this extra cost could be realized in the savings in the operating cost. Since, efficiency being the ratio of the amount of work done (i.e., output power) to the amount of energy consumed (i.e., input power), the Induction motor losses can be classified into five categories (Benhaddadi et al 2009):

- Magnetic losses that occur in the stator and rotor laminations are caused by the hysteresis and eddy current phenomena. Hysteresis losses and eddy current losses are given by Equation (2.1) and Equation (2.2), respectively.

\[ w_h = c_h B_m^x f_s \]  \hspace{1cm} (2.1)

\[ w_e = c_e B_m^2 f_s^2 \]  \hspace{1cm} (2.2)

where \( w_h \) = Hysteresis loss
\( c_h \) = Hysteresis Constant
\( B_m \) = Maximum flux density in the stator core
\( f_s \) = Frequency of flux reversals, in Hz
\( w_e \) = Eddy current loss
\( c_e \) = Eddy Constant
$x$, $c_h$, and $c_e$ depend on the quality of material with which the stator core stampings are made of.

These losses can be decreased by using better grade magnetic steel, thinner laminations and by lower flux density (i.e., larger magnetic cores), labeled as $P_c$.

- Stator and Rotor losses ($P_s$ & $P_r$) are due to currents flowing through the stator windings and rotor bars. These losses can be reduced by decreasing the conductor current density in the stator windings, in the rotor bars and in the end rings.

- Windage and Friction losses ($P_w$) are due to mechanical drag in bearings and cooling fans.

- Stray load losses ($P_l$) are due to leakage fluxes induced by load current, non-uniform current distribution, mechanical air-gap imperfection.

These losses can be reduced by design optimisation and bringing in improvements in manufacturing methods. For improving the efficiency of an induction motor, various attempts are made to reduce the watt-losses in the motors, and this study has been taken up primarily to reduce losses in submersible Induction Motor.

Relative proportion of these five loss components of an Induction Motor is dependent on the motor size. For example, the loss distribution of a 4-pole motor is as shown in Figure 2.3 (Bonnett 1994). Comparison of average loss distribution for motors tested in the Electrical Apparatus Service Association /Association of Electrical and Mechanical Trades, St. Louis. (EASA/AEMT), (Bonnett and Chuck Yung 2008), is provided in Table 2.4. Apart from this, they have analyzed all the different factors and evaluated their influences to motor performance and different dependencies between
The individual factors were carefully investigated due to the interdependence nature of each other. Sometimes, an increase obtained from one such factor may not contribute to a resultant improvement in efficiency. In addition, the cost and commercial impacts were also considered.

![Figure 2.3 Loss Distribution for a 4-pole Induction Motor](image)

**Table 2.4 Comparison of Average Loss Distribution for Motors**

<table>
<thead>
<tr>
<th>Type of Loss</th>
<th>2-pole</th>
<th>4-pole</th>
<th>Design Factors Affecting Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core loss</td>
<td>19 %</td>
<td>21 %</td>
<td>Electrical steel, air-gap, saturation, supply frequency, condition of inter-laminar insulation</td>
</tr>
<tr>
<td>Friction &amp; Windage losses</td>
<td>25%</td>
<td>10%</td>
<td>Fan efficiency, lubrication, bearings, and seals</td>
</tr>
<tr>
<td>Stator Copper loss</td>
<td>26%</td>
<td>34%</td>
<td>Conductor area, mean length of turn, and heat dissipation</td>
</tr>
<tr>
<td>Rotor Copper loss</td>
<td>19%</td>
<td>21%</td>
<td>Bar, end- ring area, and material</td>
</tr>
<tr>
<td>Stray Load loss</td>
<td>11%</td>
<td>14%</td>
<td>Manufacturing processes, slot-design, air-gap, condition of air-gap surfaces, and end laminations</td>
</tr>
</tbody>
</table>
The stray-load loss measurement represents a critical key for the correct evaluation of the motor efficiency. For this reason, a critical analysis of this type of losses has been performed. In particular, the most critical quantities that influence their evaluation, the stray-load loss sensitivity to the measurement errors were analyzed. The temperature influence, on the conventional iron losses, was experimentally analyzed. The performed tests show that the temperature difference between the no-load test and the motor real operative conditions is not negligible (Boglietti et al 2004). The work of Pillay et al (1998) enables one to avoid no load measurements while retaining the high accuracy of IEEE E-l and F-1 methods. It incorporates basic ideas of the loss segregation method, the equivalent circuit method and the genetic algorithm, as a technique for solving non-linear algebraic equations. The efficiency could be increased by improving cooling performance as well as by using better materials or by improving electromagnetic performance with better design (Yoon et al 2002). The work of Boglietti et al (2005) suggests possible modifications in the production process so as to increase the Induction Motor efficiency. This approach was called as “No Tooling Cost” (NTC) strategy as it does not require a complete redesign of new laminations and a consistent cost increment in terms of investments. But this technique is not suitable for submersible induction motors. The application of Non-linear Programming (NLP) to the design of AC induction motors driving hydraulic pumps on commercial aircrafts was proposed by Christian Koechli et al (2004). Experience shows that it doesn’t give an accurate solution. A low cost simple method proposed in (Alberti et al 2011), considers increasing the axial length of the motor core so as to meet the efficiency class limits imposed by the American and European standards. Redesigns of the Induction Motors in production were used. The stator core diameters or the slot geometries were changed, the investment costs for producing high efficiency Induction Motors can be prohibitive for small and medium companies. For these reasons, it would be interesting to analyze the low cost solutions that lead to an
improvement in efficiency. Fukuda and Morimoto (2008) proved that the difference between the efficiency of Soft Magnetic Composite (SMC) motor and that of conventional motor is only 3.7%. The induction motor made of SMC has much performance offset in that the permeability is 20% lower than the conventional electromagnetic steel, and hence results in more core loss and poor power factor. The most significant changes to the loss in Induction Motors caused by the repair were stator copper loss, core loss, and stray load loss (Cao et al 2004).

The Hooke-Jeeves search routine is used for optimisation and three objective functions, namely, efficiency, efficiency-cost, and cost are considered (Jawad Faiza and Mohammad 2001). Some performance characteristics of the industrial design are very close to those of optimum cost design. Performance variations of the industrial design are similar to those of optimum efficiency design, although the industrial design has a lower efficiency. Hamid et al (2006) proposed the application of Particle Swarm Optimisation (PSO) towards minimization of losses and operating cost in the Induction Motor Drives. In this method, two strategies towards speed control of induction motor were proposed. Those two strategies were based on PSO and are referred to as Maximum Efficiency Strategy and Minimum Operating Cost Strategy. The proposed technique was based on the principle that the flux level in a machine can be adjusted so as to get minimum amount of losses and operating cost for a given value of speed and load torque. Efficiency optimisation of Induction Motor Drive using Genetic Algorithms was proposed by Rouabah et al (2008), by adjusting the magnetizing current component with respect to the torque current component in order to minimize the total copper and iron losses of the machine.

Submersible Induction Motor is a special type of induction motor, and its design and specifications are slightly different from those of the
conventional induction motor. The heat which is generated within the windings and squirrel-cage rotor is removed with the help of the water filled into motor, and thus lubrication of the rotating parts of the motor is provided. While the diameter and the length of the Induction Motor varies with certain ratio, the diameter in submersible motors remains constant; but length can be extended. The extreme extension of the length of the motor brings in some difficulties in terms of manufacturing it mechanically. Optimisation methods are employed in sizing and computation of parameters of submersible motor. Parameters such as main dimensions, motor diameter, and core stack length are computed during design for optimisation. The design optimisation of submersible induction motor based on Genetic Algorithms (GA) and Finite Element Method (FEM) was performed considering torque equation as the objective function (Cunkas et al 2011). The results obtained from GAs were compared with those of FEM, as the motor performance was analytically calculated by using equivalent circuit and independent variables. The FEM analysis provides an opportunity to investigate the effects of geometric variations, non-linearity of magnetic materials, and eddy currents on motor performance. The optimisation results have indicated that there was a significant improvement in the performance of the optimised motor compared to the existing motor. In these methods, the improvement in efficiency is not in proportion to the cost involved in manufacturing.

The influence of the skin effect and saturation on the rotor resistance, magnetizing, and leakage reactances were studied using Newton-Raphson algorithm. Handy expressions that can predict the machine parameters as functions of the slip have been derived (Akbaba et al 1995). Problems of traditional efficiency optimisation methods were: efficiency optimisation could not be realized as the appropriate flux could not be produced under complex work conditions, as induction motor parameters were variable and non-linear under such conditions. The characteristics and
calculation method of EMD-EKF (Empirical Mode Decomposition-Extended Kalman Filter) were analyzed. EKF with EMD method had both of their respective advantages, which could improve the accuracy of estimates (Chen Peng et al 2011).

Pil-Wan Han et al (2008) have shown that Design of Experiments (DOE) can be used to the design of some factors of a three-phase induction motor so as to maximize the efficiency. The fractional factorial designs were used for the screening of six design factors and the Response Surface Methodology (RSM) was applied to get the efficiency-maximized points from the screened four factors. The design was also performed to consider the flux density of the stator and rotor teeth. Simulations based on the equivalent circuit of induction motor were used to obtain the responses for DOE. The efficiency of the initial model got improved by 3.3% without increasing motor volume and electrical steel grade. FEM-based design of an Induction Motor’s Part Winding to reduce the starting current was proposed by Stermecki et al (2006).

Boglietti et al (2007) proved that there is an increase in efficiency by 1.5%, if the copper rotor is manufactured using investment casting technological process. Substituting copper for aluminum in the rotor squirrel cage is a central strategy towards reaching substantially higher efficiency in the induction motors (Peters et al 2007). Short die-life has discouraged production of copper rotors; but, recent development of a heated nickel-base alloy die-technology has solved the manufacturing problem; but, with increased production cost. Francesco Parasiliti (2005) presents a comparison between four different design strategies with the aim of improving the efficiency of three-phase induction motors: substitution of die-cast copper cage for aluminium cage with “standard” and “premium” electrical steels; design optimisation of copper cage motor by changing the stator winding and
the stack length only; design optimisation of copper cage motor by changing
the stator winding, the stack length, and the stator and the rotor slot shapes.
The comparison was based on the actual efficiency improvements, the
arrangement of the motors with respect to the European Classification
Scheme (EC/CEMEP), the contribution of each material and innovative
technology. The results are concerned with 4-pole, 50 Hz, 400 V, TEFC,
3 kW and 15 kW induction motors.

Fireteanu et al (2007) proposed an optimal design of squirrel cage
rotor slots and copper bars of high power induction motors with respect to the
values of starting torque, breakdown torque, efficiency, power factor, and
rotor heating. Criteria for evaluation of optimal geometry of rotor bars and of
optimal value of the cross-section area of the bars were studied. For high
efficiency, die-cast copper rotor cage was used in single-phase induction
motors by Kwangsoo Kim et al (2009); but, increase in efficiency is small and
starting torque is reduced largely due to higher conductivity of copper. This
study was based on the parametric analysis method and the Finite Element
Analysis (FEA) of the induction motor.

Four types of rotor constructions, namely, Aluminum die-cast
(AIDC), copper die-cast (CuDC), fabricated aluminum bar (AlBar), and
fabricated copper bar (CuBar) were analyzed by Finley and Hodowanec
(2000) and concluded that it is possible to select the optimal rotor
construction method (one that will yield the desired reliability at the lowest
cost) for a particular application. Manoharan et al (2010) proposed a method
to increase the efficiency of submersible pump-sets by increasing the
efficiency of squirrel cage induction motor using Die-cast Copper Rotor
(DCR) technology. A new rotor slot-design was proposed instead of the
conventional slot-design for accommodating copper conductors in rotor.
Possible efficiency improvements were checked with three varieties of
laminations. The various electrical parameters, including the low voltage performance, were measured and compared with those of the existing Copper Fabricated Rotor (CFR). The overheating of rotor stamping during Die-cast process results in the failure of the lamination insulation over a period of time, particularly, in submersible motor, and this has been reported by manufacturing Industries.

The optimal stator-slot-shape for good efficiency design for the six-step inverter-fed induction motor was proposed by Jae-Woo Kim et al (2005). This design method was implemented and analyzed, in which the FEA on stator one phase band model was coupled with harmonic equivalent circuit analysis method. By this design method, the initial stator-slot-shape was changed to optimally-designed stator-slot-shape; i.e., the height of the slot and the width of the stator teeth were increased. As a result, the motor efficiency got improved and harmonic loss was reduced. Zhou Rui et al (2010) have described the optimal design of the stator slot of a single-phase induction motor based on Maxwell 2-D RMxpert. The key point of single-phase induction motor optimisation lies in the handling of the magnetic field; i.e., by optimizing the main and the auxiliary-phase winding impedances and the phase angles so as to change the angle between the main and the auxiliary phase currents, and hence, making the shape of the magnetic field as round as possible. This was the main work of single-phase induction motor optimisation. Selecting appropriate stator and rotor slot dimensions can improve the motor performance in a small scale. However, the slot dimensions are more complex with other parameters, and the slot must be designed according to the winding; so the aided-design is often used by designing slot after winding optimisation.

The slotting of an electrical rotating machine creates slot-harmonics in the air-gap magnetic flux density. These slot-harmonics are the source of a
non-negligible part of the Unbalanced Magnetic Pull (UMP) that results in noise and vibrations in the motor. Burakov and Arkkio (2007) presents analytical justifications for the use of a numerical impulse method to calculate the effects of the slot-harmonics on the UMP. This method was then used to show that the force components due to the slot-harmonics cannot be reduced easily. The shape of the stator slot of a 3-phase cage induction motor for the reduction of iron-loss was then presented. For optimum shape design, the sensitivity analysis by discrete approach is employed and the Gradient Projection method for non-linear constraint problems was chosen for optimisation. The 2-D finite element method with voltage source was used to find the flux distribution in induction motors (Seok-bae Park et al 1995). Due to the fringing effect, the magnetic flux in the air-gap of electrical machines was shown to have got reduced. This leads to larger effective air-gap length. For this reason, in the design stage of the electrical machines, a larger magnetic flux must be chosen. On the other hand, magnetic loading must be taken smaller than the value corresponding to the actual air-gap length. Currently, Carter coefficient is applied so as to compensate the slots effects. This coefficient was calculated with respect to the slot dimensions and air-gap length, using Carter formulae and corresponding curves. These curves were taken by solving the 2-Dimensional Laplace equation for voltage, and cannot be accurate (errorless) completely. FEM packages of numerical methods have been used to calculate carefully, slot effects on the air-gap flux distribution (Mohammad B. B. Sharifian et al 2009). All the above said methods describe techniques for improving the efficiency of the induction motor, which are either costlier or difficult to implement the manufacturing process in small-scale and medium-scale manufacturing industries which manufacture agricultural-motors.

Enhanced use of groundwater has led to wells being bored increasingly deeper, and farmers requiring higher-capacity pumps to lift
water. This extraction has not only increased the costs to the farmers and the utilities, but progressively worsened water availability in various regions of the country as assessed by the Central Ground Water Board (John Kurien et al 2006), Surveys had been conducted regarding access to groundwater (Rakesh Kumar et al 2005), costs of well-irrigation, impacts of water-level decline, etc. In most of the places, the submersible pump-sets operate with less water output due to scarcity of water in bore-wells. The water is stored in mud-based reservoirs and then it is being used for crops, and that increases the energy consumption. To improve utilization, speed control of pump on the basis of its discharge assumes importance. Efficient variable-frequency control of the centrifugal- pump-drive motor was proposed by Pottebaum and Joseph (1984), to control fluid by a throttling-valve or a bypass-valve in many applications. A submersible motor with an advanced delta-modulated inverter driver was proposed by Maswood et al (2006). Since tacho feedback or other traditional speed sensing means is not permissible in a sealed motor or a pump, a sensing method was used to monitor the motor speed from the terminal quantities like voltage, current, and the input power factor. A semi-closed loop operation of the motor was proposed. Rodriguez Arribas and Vega Gonzalez (2002) proposed a control system for the centrifugal pump and fan drives, based on induction squirrel-cage motors. It has been proved that the Pontriagin’s maximum principle can be applied to the drives with parabolic dependence between the load torque and the speed, in order to minimize the duration of the transient, when the motor passes from one maximum efficiency steady-point to another with limited stator current. The optimal trajectories of the motor variables for different combinations of initial and final steady-stages were defined.

Drip Method of Irrigation (DMI) introduced to improve the efficiency of water usage is being practiced in different parts in India, since early eighties. Quite a few studies have analyzed the impact of drip method of
irrigation on water use efficiency, water saving, cost of cultivation, productivity of crops, etc., using both experimental-level and farm-level survey data in India. However, studies have not analyzed the linkages between the adoption of DMI and electricity use in different crops using farm-level survey data in Indian agriculture. DMI reduces the working hours of pump-sets through water saving and therefore, it reduces the consumption of electricity and also increases the efficiency of electricity use substantially (Narayanamoorthy 2006). Ramachandra Murthy and Ramalinga Raju (2009), have studied the inter-linkages between agriculture and Electricity. This literature survey shows that no work has been done so far, so as to sense the flow of water at the outlet of the pump, towards conservation of energy.

2.4 REVIEW OF DESIGN AND APPLICATIONS OF SWITCHED RELUCTANCE MOTOR

Switched Reluctance Motor (SRM) has been a remarkable exploration in the field of electrical engineering. It has numerous advantages over conventional machines. Looking from the energy perspective, SRM is very much suitable for high torque-speed applications. The following literature survey describes the different applications of SR Motor, issues and constraints related to its design.

A variable-speed, 120-HP motor drive system for an electric-motor-driven, large aircraft engine fuel pump application was described by Radun (1992). The drive runs from 270 V DC, which was the emerging power standard for aircraft power. The intended load of the drive was a centrifugal pump, although all system testing was done on a dynamometer test stand. The Brushless DC (BLDC) motor is used as spindle motor in a hard-disk-drive system. The higher cost of rare-earth permanent magnets and the complexity of its controller are some of its disadvantages. Its performance also deteriorates in small-format-disk-drive systems. Low et al (1995) proposed a
4-phase (in-hub) miniature switched reluctance motor with the outer rotor structure for the spindle motor in 3.5" hard-disk-drive. The design methodology and related constraints have been described. The magnetic characteristics, flux-linkage, inductance, co-energy, and static torque have been calculated using 2-D finite element analysis. The field solutions and the analysis on electric circuit have been processed to give the description of the dynamic-state performance of the prototype. The work by Liuchen Chang (1996) describes the design procedure of switched reluctance motors used in automobile applications. In the process, empirical method, finite element method, and analytical method have been applied. The empirical formulae as established by design experts yield a preliminary design. The finite element method accomplishes fine-tuning of the design and validation. The analytical model as established by the generalized electrical machine theory enables study of converter control and dynamic performance. The investigation by Rahman et al (2000) shows the capabilities of Switched Reluctance Motor for Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) applications. This investigation was carried out in two steps. The first step involves the machine design and the application of finite element analysis to obtain the static characteristic of the motor. In the second step, the finite element field solutions were used in the development of a non-linear model to investigate the dynamic performance of the designed motor. The research work by Chen Hao et al (2002) was fuzzy-based PWM implementation to control the speed of the existing SR motor for bicycle applications. A novel 2-Dimensional (2-D) Planar Switched Reluctance Motor (PSRM) for position control applications was developed by Pan et al (2006). The 2-D planar motor has the advantages of simple mechanical construction, high reliability, and the ability to withstand hostile operating conditions. Due to the unique structure of the magnetic circuit of the planar motor, there was very little coupling between the X-axis and the Z-axis, and no decoupling compensation was needed. This
innovative SR planar motion system was an ideal replacement for traditional X-Y tables in industrial automation applications.

The work by Ekram et al (2007) shows the design and development of a high efficiency 3-phase, 6/4-configuration SRM for driving a 280 W mixer-grinder. The conventional universal motor, which has a poor efficiency in the range of 70%, was replaced with SRM. The designed SRM delivers the same power at the rated speed of 10000 rpm with much higher efficiency of 86%. A low-cost energy-efficient variable-speed drive for high-volume applications, such as home-appliances, fans, and hand-tools were developed by Jaehyuck Kim and Krishnan (2009). A new low-cost power converter was proposed, and the drive system was realized using a two-phase switched reluctance motor. A new low-cost Hybrid Switched Reluctance Motor for adjustable-speed pump applications was proposed by Kaiyuan Lu et al (2011). The motor was a single-phase motor, driven by a unipolar converter, which uses both the reluctance torque and the permanent magnet interaction torque. Compared with conventional single-phase switched reluctance motors, it has an increased torque density. The cogging torque was beneficially used in this motor for reducing the torque ripple. It was demonstrated that such a motor drive system can be a suitable candidate to advantageously compete with the existing motor drive systems for low-cost applications. Brauer et al (2009) derived the model for Switched Reluctance Motor used in a in household applications and it has been analyzed through the 3-D magnetostatic analysis and 3-D finite elements methods. As a result of the analysis, phase inductance, torque ripple, average and instant torques, air-gap power, and magnetic flux pattern values have been obtained.

Andrada et al (2012) have presented the efficiency and electrical energy consumption of switched reluctance motor drive with a commercial vector-controlled induction motor drive of the same size. An experimental
result shows that the proposed one is a good choice for applications that require slow varying loads and energy savings. The switched reluctance motor is well known for its higher acoustic noise, caused by stator vibrations. Techniques for noise reduction require knowledge of the modal frequencies, which depend on mechanical shapes and dimensions, as well as material properties. The effects of Young’s Modulus, equivalent mass, Poisson’s ratio, and stator-core lamination stacking factor are the major factors that contribute to vibrations in SR motors (Zhangjun Tang et al 2003).

Praveen Vijayraghavan (2001) and Krishnan et al (1988) have provided the detailed design procedure of SR motor. Pavol Rafajdus et al (2004) have presented an analytical method for the calculation of some important SRM parameters such as inductance, flux linkage, and torque. The calculation is based on the description of the magnetic flux line profile and its length, and the areas under which the magnetic flux penetrates the iron and air-gap parts. The work outlines the procedure as to how to determine typical magnetic flux lines and formulates the expression for their lengths and corresponding areas to be able to calculate the reluctance and hence, inductance for a certain current and rotor position. The information pertaining to the position of the rotor is used to drive the SRM. However, for a simple driving system that doesn't require precise control, it is not advisable to use expensive encoders. Opto-interrupter and slotted-disk were introduced by Becerra et al (1993), Se-Joo Kim et al (2004) and Yong-Ho Yoon et al (2005). It is an economic method only when common analog devices are used for the control circuit, making the process more economical. The work by Faiz et al (2006) and Jahan et al (2011) proves that the optimal design of SR Motor is possible through ANSYS package. A parametric simulation model for SRM has been developed, analyzed for optimal design of this motor. The major electromagnetic characteristics of SRM such as static torque and instantaneous phase current were predicted using this simulation model.
Although Finite Element (FE) calculations are 2-Dimensional, simulated results were in agreement with experimental results.

Centrifugal loads like Fan, Blower, and Water-pump have non-linear rising characteristics. The torque requirement for this application is given by Equation (2.3).

\[ T_L = T_r + (T_m - T_r) \left( \frac{N^x}{N_{n}^x} \right)^x \]  

(2.3)

where  

- \( T_L \) = Total torque demanded by the machine at a speed of \( N \) rpm.
- \( T_r \) = Resistive torque demanded by the machine in moving parts.
- \( T_m \) = Resistive torque demanded by the machine when it is driven at its normal speed of \( N_n \) rpm.
- \( x \) = Exponential coefficient, characterizing the change in resistive torque with change in speed (For non-linear rising characteristic; \( x = 2 \)).

SR Motor speed-torque characteristic matches with this requirement. No work has concentrated so far on this application. The literature discussed provides enough input to design a suitable SR Motor configuration for submersible pump-set applications.