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Research article

Numerical Simulation and Design Parameters in Solar Photovoltaic Water Pumping Systems

Prof. (Dr.) V. N. Maurya
Professor & Principal,
Shekhawati Engineering College, Rajasthan Technical University, India
E-mail:prof.drvnmaurya@gmail.com, prof_vnmaurya@yahoo.in

Diwinder Kaur Arora
Inspector of Police,
Group Centre, Central Reserve Police Force, Lucknow-226002, U.P.
Ministry of Home Affairs, Govt. of India
E-mail: hkdkarora@rediffmail.com, diwi.kaur1992@gmail.com

Er. Avadhesh Kumar Maurya
Assistant Professor, Department of Electronics & Communication Engineering
Lucknow Institute of Technology, U.P. Technical University, Lucknow-226002, India
E-mail: avadheshmaurya09@gmail.com

Ram Asrey Gautam
Assistant Professor, Department of Applied Mathematics
Lucknow Institute of Technology, U.P. Technical University, Lucknow-226002, India
E-mail: ragpmc08@yahoo.com

Abstract

Present paper envisages an empirical model for solar photovoltaic water pumping systems. In this paper, we have developed relationships between Array power and Borehole depth, per capita water use and Rainfall and Borehole depth and Capital cost of owning solar photovoltaic water pumping systems (SPWPS) in Nigeria. The sample data used in our present study was obtained from questionnaires administered on randomly selected respondents involved in the design construction and funding of SPWPS projects in Nigeria. The Pearson product moment correlation, linear regression and the Student t-test statistic are used as fundamental methodological tools in order to simulate and design the solar photovoltaic water pumping systems. The results obtained in our current study suggests that at 0.05 level of confidence, linear relationships exist between: Array power and Borehole depth, Per capita water use and the Rainfall of a location and Borehole depth and Initial capital cost. Further improvements in the model performance require input from more detailed meteorological, site evaluation and cost information.

Keywords: Simulation, design construction, solar photovoltaic water pumping system (SPWPS), Moment correlation, linear regression, level of confidence, Student t-test statistic, initial capital cost.

1. Introduction

The facility of clean water in the required quantity for both domestic and animal use is a pre-requisite and vital for good healthy living, reduction in mortality rate and economic growth of every nation. Requirement of potable water for domestic and animal use befits even more imperative for developing countries such as India, Bhutan and others as assessed by the United Nations Environment Programme [13]; UNEP estimated that about 80 per cent sicknesses are related to unsafe drinking water. The capacity to prospect, exploit and supply potable water by these developing countries is hampered by the economic crisis facing them, which has resulted in low incomes and poor living conditions of their people and reduced government revenue also as assessed by the World Bank [12]. However, within tight budgetary constraints and limited resources, these countries have managed to provide this resource using various usual techniques such as hand pumps, wind pumps, gasoline/diesel pumps and lately, solar photovoltaic pumps (SPVP). Each of these usual techniques to facilitate potable water to people has its advantages and disadvantages and the most widely used gasoline/diesel pumps have high operating and maintenance costs in spite of pollution of the environment at large scale. Although, solar photovoltaic pumps (SPVP) have high initial owning cost, concerns for the environment, minimum operating cost, cost effectiveness in small power applications up to 40kW in remote rural areas and reliability have tended to increase its widespread application, for more details, we refer to Porsoski [10]. Very recently Maurya et al [5] confined their attention to develop a mathematical model for annual maximum rainfall with Gumbel and Frechet distributions using parameter estimation techniques in order to highlight the scope of rainfall water resource.

Principally, the SPVP system comprises of an array of modules with support structures, electric motor that operates a pump and connecting pipes and electric cables. The pump mechanically lifts water from boreholes or open channels unto an overhead storage tank from where water is gravity-fed to users. The photovoltaic process – the transformation of solar energy into electrical energy widened the horizon for increased energy supply especially for developing countries, which are located in the tropical zone having the highest abundance of input solar radiation. However, the euphoria, which greeted this new technology, has not been matched by widespread application, due probably to its high owning cost and lack of awareness of its potentials. Solar photovoltaic water pumping technology was introduced into Nigeria in 1982 by Kano State government as a pilot project. The success of the scheme led the Federal, State and Local Governments, Aid Agencies and individuals to install SPVP systems such that by the end of 2003, about 600 systems had been installed, Okonta et al. [9]. The general characteristics of SPVP sub-sector in Nigeria has been the dominant role played by government and its agencies in the funding and installation process, accounting for 93.7 per cent of all systems while individuals and Aid Agencies financed and installed 6.3 per cent. Individuals and manufacturer's representatives import the PVP systems and their component parts into the country at high duty cost while government agencies and contractors do the installations. All the PVP systems installed by Government and Aid Agencies are used to supply potable water free-of-charge to beneficiaries of such projects for domestic uses and animal watering. No entrepreneur has installed any SPVP system in Nigeria for the purpose of profit taking. All the SPVP systems are completed and handed over to the benefiting communities as "turnkey" projects without the participation of the communities at any stage of the project development. It is also important to note that government makes no provisions for the operation, maintenance and repair of the SPVP systems constructed and handed over to benefiting communities. Apart from the world-wide most singular problem of high initial capital cost, the level of adoption of SPVP technology in Nigeria is plagued by additional problems of inadequate design data, limited number of technicians with appropriate experience in SPVP construction, operation and maintenance, lack of awareness of the potentials of the technology; for more details we refer Okonta et al [7]. These problems are compounded by paucity of data and information related to laboratory and field-testing performance of systems and components, their operating characteristics in Nigeria environmental conditions and causes of failure. A few research works had been done to address some of these problems.

Aliyu and Sambo [3] investigated the performance of a SPVP system under varied climatic conditions ranging from cloudy, dusty to clear days. They concluded that the system performed most satisfactorily in clear days and poorly in dusty and cloudy days and recommended that on such cloudy days, storage batteries could be incorporated into the system. Bajpai et al [4] and Siyanbola et al [11] obtained similar results. However, it is observed that incorporating batteries into the system would increase the cost of an already expensive system.

Ogedegbe [6] carried out a cost-benefit analysis of capital, operation and maintenance costs of solar – PVP with diesel powered pumping system. He found that the PVP broke-even with diesel powered system in three and half years. Cost-benefit analyses are suitable for government investments because the emphasis is predominately on benefits rather than profits. Life-cycle-cost analysis would be more appropriate to investments where returns are expected in monetary terms.

Okonta et al [9] carried out an assessment of the socio-economic and institutional impact of SPVP system on the inhabitants of Oloki village, located in south western Nigeria. They reported that the application of the system resulted in the eradication of major water-borne diseases prevalent in the village and also strengthened their capability to participate in development projects.

In the present paper, an empirical model for solar photovoltaic water pumping systems has been established which can be simulated to provide data and information on important design inputs and can be used also in the estimation of the total initial capital cost of owning a SPVP system in Nigeria and other developing countries.

2. Methodology Used for Cost Analysis

The study involved the administration of different sets of validated questionnaires on randomly selected respondents including experts lying in the categories of engineers, hydro-geologists, technicians, researchers and contractors in charge of SPVP design, construction, repair and maintenance. Other groups include manufacturers 'representatives and vendors in SPVP business and government officials involved in SPVP funding and installation. The data collected has already been analyzed using Pearson product moment correlation, regression, Student, t-test statistic and statistical package for social science (SPSS).

3. Simulation and Empirical Modeling

3.1. Relationship between Array Power and Borehole Depth

Data on Array power (kWp) and their corresponding borehole depths were obtained for some SPVP systems spread across the whole country as shown in Table 1. The application of a Pearson product moment correlation and linear regression gave the relationship between Array power and Borehole depth as

$$\text{Array power} = 0.02\,(\text{borehole depth}) + 0.44 \qquad \text{.................. (3.1)}$$

Equation (3.1) is both predictive as well as a transfer function involving the two most important design parameters, Array power and Borehole depth and hence can be considered as a fundamental expression through which the relationship between Array power and Borehole depth is established. It has the following implications.

It relates the electrical energy conversion capacity to the mechanical energy response section and hence gives an intrinsic indication of the total efficiency of the system.
It is possible to estimate the number of modules, which can be used for a particular application when the borehole depth is known. This reduces the amount of time and material resources expended in obtaining design data and invariably reduces the cost of constructing new PVP systems hence improve adoption rate.

3.2. Relationship between Water Consumption Rate and Precipitation

The Pearson Product Moment Correlation was applied to the values of precipitation in different part of the country and their corresponding values of per capita water consumption as shown in Table 2. Again applying a linear regression analysis the relationship between water consumption and precipitation as:

$$\text{Per capita water use} = 0.0065\,(\text{rainfall}) + 14.82 \qquad \text{..................... (3.2)}$$

Thus, if the annual rainfall of a location is known in Nigeria, equation (3.2) can be used to estimate the per capita water use. This hence makes it possible to estimate the water demand of a location for PVP design purposes. Rainfall figures for different locations in Nigeria are fairly well documented and population figures are equally updated at regular intervals, hence the disparity introduced by using equation (3.2) is low. This again provides very important design data (water demand) without incurring huge expenses. Accurate estimation of the water demand of a location is a critical factor in the reliability of any PVP system because it leads to user satisfaction and social acceptability, which ultimately results in widespread application of the technology.

3.3. Relationship between Capital Cost and Depth of Borehole

Worldwide, the total initial investment cost of owning a PVP system had always hindered its widespread application. The PVP technology is completely alien to Nigeria and its level of adoption is hence dependent on the ability to raise the required foreign capital to cover the cost of components including high import duty costs. The investor in the PVP sub-sector in Nigeria does not enjoy incentives, subsides and rebates provided by the Nigerian Industrial Policy because no local manufacturing of components is undertaken, Okonta et al [9].

The process of installing PVP systems in Nigeria involves competitive bidding by Contractors but most government agencies have no capacity to verify spurious claims by Contractors. Again, the wide gap between capital cost of Federal and State Government PVP projects necessities a careful scrutiny with a view to reducing these disparities. Data were collected from contractors and government officials responsible for PVP Project funding and installation as shown in Table 3 and 4 respectively. A Depth – Cost analysis was carried out on data provided using Pearson Product Moment Correlation and student t test. A further application of linear regression analysis level of confidence and 20 degrees of freedom showed that the difference between the means of the two sets of uncorrelated data i.e data supplied by contractors and government officials were not statistically significant showed that a relationship given as:

$$\text{Capital cost} = 0.0544\ (\text{Borehole depth}) + 1.506 \qquad \text{..........................} \ (3.3)$$

exists between Capital costs of PVP systems in Nigeria and Borehole depths. A measure of confidence building can hence be introduced into the costing process of PVP business in Nigeria by the application of equation (3.3) as a general basis for arriving at reasonable cost estimates of PVP systems when the borehole depths are known. Equation (3.3) is significant because it relates the technical aspect of PVP with its economic implications. At worst, this equation acts as a rule – of thumb index for arriving at PVP investment costs when the borehole depth can be estimated or is known.

3.4. Capital Cost Modeling

This study allowed the configuration of the total initial capital cost of a PVP system by considering cost contributions from module, motor-pump set, inverter, pipe/electrical work, installation and borehole construction. It was found from the model chart displayed in Fig 1.1(a) that the two most expensive components of PVP systems in Nigeria are the module and borehole construction with 33 and 28 percentage share of the total capital cost respectively. Other, in decreasing percentage cost include; motor-pump set (14%), inverter (10%), installation work (8%) and pipe/electrical work (%).

This compares favorably well with the outcome of an International Programme for field-testing and demonstration of PVP systems carried out in seven developing countries (Argentina, Brazil, Jordan, Indonesia, Philippines, Tunisia and Zimbabue) by GTZ (1996) as shown in Fig. 1.1 (b) It should be noted that Fig. 1.1(b) was constructed without provision for borehole construction cost. If the cost construction cost is removed from Fig. 1.1(a), the widest disparity in module cost between the charts becomes 23% while the other costs become comparable.

Table 1: Design data for some selected photovoltaic water pumping systems

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Year of Installation	1993	1999	1999	1999	2000	2000	2000	2001	2001	2001	2002	2002	2003	2003
Array Power (kWp)	0.76	0.36	3.76	2.46	0.76	2.60	2.64	0.76	0.76	0.40	2.00	1.96	0.76	1.92
Borehole Depth (m)	42.0	10.0	60.0	35.0	50.0	90.0	91.4	60.0	30.0	20.0	125.0	60.0	52.0	36.6
Number of Modules	24	4	24	32	24	30	22	32	4	8	32	32	32	24

Table 2: Variation of annual rainfall with per capita water use

S. No.	1	2	3	4	5	6	7	8
Annual Rainfall	650.0	900.0	1000.0	1270.0	1388.0	1500.0	1950.0	2285.0
Per Capita Water	21.55	13.93	19.70	24.29	21.05	32.17	20.19	31.33

Table 3: Initial investment costs of selected photovoltaic water pumping systems from Contractors

S. No.	1	2	3	4	5	6	7	8	9	10	11	12
Year of Installation	1989	1994	1997	1997	2000	2000	2001	2001	2001	2001	2002	2003
Borehole Depth (m)	34.0	80.0	39.0	134.0	45.0	40.0	70.0	70.0	65.0	39.0	45.4	16.0
Initial Cost ($N10^6$)	2.00	3.48	2.00	8.00	5.50	5.80	3.00	3.00	3.00	2.40	5.12	2.50
Initial Cost Corrected ($N10^6$)*	7.60	8.21	3.54	14.17	7.32	7.72	3.63	3.63	3.63	2.90	5.63	2.50

*Corrected for time value of money up to 2003

Table 4: Initial investment costs of selected photovoltaic water pumping systems from Government officials

S. No.	1	2	3	4	5	6	7	8	9	10
Year of Installation	1999	2000	2000	2000	2001	2001	2001	2002	2002	2003
Borehole Depth (m)	10.0	50.0	90.0	100.0	60.0	24.0	20.0	125.0	61.0	52.0
Initial Cost ($N10^6$)	0.70	4.12	2.80	2.30	6.00	2.00	1.10	10.0	2.30	9.46
Initial Cost Corrected ($N10^6$)*	1.02	5.48	3.73	3.06	7.26	2.41	1.33	11.0	2.53	9.46

*Corrected for time value of money up to 2003

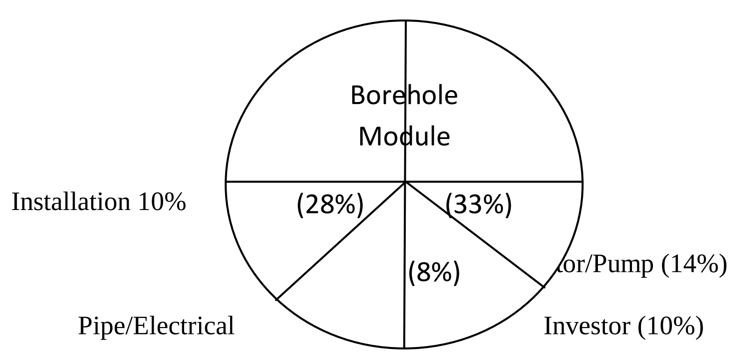

Fig. 1.1(a): The model chart

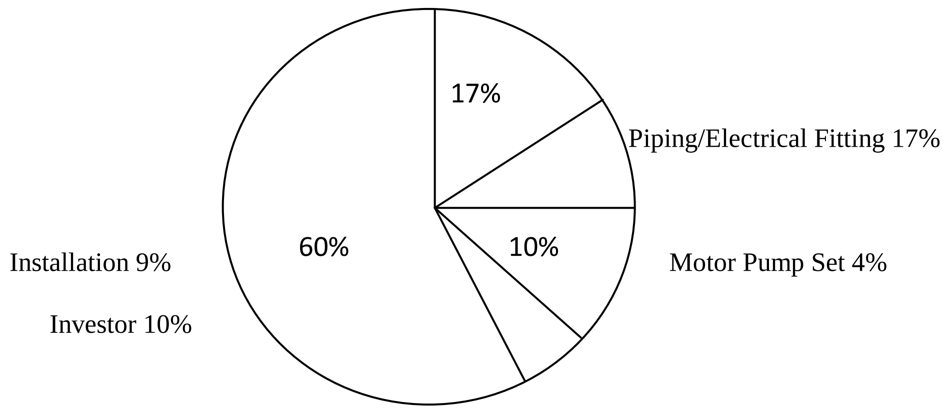

Fig. 1.1(b): Pie chart of component capital cost (Source; GTZ Energy Division, 1996)

4. Conclusion and Policy Recommendation

This paper enables an empirical model for solar photovoltaic water pumping systems and mathematical relationships among major design parameters have been established which are ultimately useful to reduce site visitations in remote rural areas with its attendant high costs in terms of transportation and time. Data acquisition and computation periods are also reduced. This is desirable for poor developing countries such as India, Bhutan, Nepal, Nigeria where access to meteorological and cost information increases the capital cost of owning solar photovoltaic water pumping systems. The outcomes of our present study are presented and discussed in the sub-sections 3.1-3.4. However, applications and subsequent refinements in the established models become imperative for further development and optimization of the design, construction, operation and maintenance of PVP systems in Nigeria. This would lead to increased technical performance, reliability and cost-effectiveness and hence to increased adoption of the PVP technology.

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Acknowledgements

Dr. V. N. Maurya; author of the present paper has served as founder Director at Vision Institute of Technology, Aligarh (Uttar Pradesh Technical University, Lucknow (India). Prof. V. N. Maurya is one of the Indian leading experts in Mathematical and Physical Sciences and Operational Research and he has made significant contributions to many mathematical, statistical, computer science and industrial engineering related areas basic as well as application oriented. Formerly he has served as Principal/Director at Shekhawati Engineering College (Rajasthan Technical University, Kota) and also as Selected Professor & Dean Academics at Institute of Engineering & Technology, Sitapur, UP, India. He earned his M.Sc. and Ph.D. Degree in Mathematics & Statistics with specialization in Operations Research with First Division from Dr. Ram Manohar Lohia Avadh University, Faizabad, UP, India in the year 1996 and 2000 respectively and thereafter he accomplished another two years Master's Professional Degree-MBA with First Division (B+ Grade) with specialization in Computer Science from NU, California, USA in 2003. Ph.D. Thesis titled as "***A study of use of stochastic processes in some queueing models***" authored by Dr. V. N. Maurya under supervision of Prof. (Dr.) S.N. Singh, Ph.D. (BHU); was offered to publish in **Scholar's Press Publishing Co., Saarbrucken, Germany** in view of his excellent research work. Since his primary education to higher education, he has been a meritorious scholar and recipient of meritorious scholarship. He started his teaching career as Lecturer in 1996 to teach post-graduate courses MBA, MCA and M.Sc. and later he was appointed as Professor & Head, Department of Applied Sciences and Engineering at Singhania University, Rajasthan in the year 2004. Since then, Prof. V. N. Maurya has rendered his services as Professor & Head/Dean as well as keen Researcher for Post-Doctoral research and he has spent his entire scientific and professional career in teaching at various premier technical institutions of the country such as at Haryana College of Technology & Management, Kaithal (Kuruchhetra University, Kuruchhetra); Institute of Engineering & Technology, Sitapur and United College of Engineering & Research, Allahabad. On the basis of significant research work carried out by him in the last 17 years of his professional career, Prof. V. N. Maurya has published more than 50 scientific and academic research papers including 25 research papers as Principal Author based on his Post-Doctoral work and D.Sc. Thesis in Indian and Foreign leading International Journals in the field of Mathematical and Management Sciences, Industrial Engineering & Technology. Some of his published research papers in India, USA, Algeria, Malaysia and other European and African countries are recognized as innovative contributions in the field of Mathematical and Physical Sciences, Engineering & Technology. Prof. V. N. Maurya is an approved Supervisor of UGC recognized various Indian Universities for Research Programs leading to M. Phil. & Ph.D. such as Shridhar University, Pilani (Rajasthan), Singhania University, Rajasthan

and CMJ University, Sillong, Meghalaya and JJT University Jhunjhunu, Rajasthan and U.P. Technical University Lucknow etc. and since last 7 years, he is actively engaged as Research Supervisor of M. Phil. & Ph.D. Scholars in wide fields of Operations Research, Optimization Techniques, Statistical Inference, Applied Mathematics, Operations Management and Computer Science. He has guided as Principal Supervisor and Co-Supervisor to several Research Scholars of M. Phil. and Ph.D.

Apart from this, in the course of his distinguished professional career, Dr. Maurya has been appointed as Head-Examiner by leading Indian Universities-U.P. Technical University, Lucknow during 2005-06 and Chhatrapati Shahu Ji Maharaj University, Kanpur for three terms during 2000-2004 for Theory Examinations of UG and PG Programs for significant contribution of his supervision in Central Evaluation. On the basis and recognition of his knowledge and significant scientific and academic research contributions in diversified fields of Mathematical and Management Sciences as well as Engineering & Technology, Prof. V.N. Maurya has been the recipient of Chief-Editor, Member of Editorial and Reviewer Board of many leading International Journals of USA, Italy, Hong Kong, Africa, Austria, India and other countries such as World Journal of Applied Engineering Research, Academic & Scientific Publishing, New York, USA; American Journal of Engineering Technology, New York, USA; Open Journal of Optimization, Scientific Publishing, Irvine, California, USA; International Journal of Operations Research, Academic & Scientific Publishing, New York, USA; American Journal of Applied Mathematics, Science Publishing Group, New York, USA; American Journal of Theoretical & Applied Statistics, Science Publishing Group, New York, USA; Science Journal of Applied Mathematics & Statistics, Science Publishing Group, New York, USA; International Journal of Industrial Engineering & Technology, USA; International Journal of Operations Research, USA; International Journal of Electronics Communication and Electrical Engineering, Malaysia; International Journal of Statistics and Mathematics, USA; International Journal of Information Technology & Operations Management, USA; International Journal of Advanced Mathematics & Physics, USA; Physical Sciences Research International, Nigeria (Africa); International Journal of Applications of Discrete Mathematics, New York, USA; Science Journal Publications, Nigeria; Wyno Journal of Engineering & Technology Research, India; Wyno Journal of Physical Sciences; Wyno Journal of Engineering & Technology Research; Modelling & Simulation, Engineers Press Publishing Group, Vienna, Austria; European Science Journal, World of Engineering Sciences, Austria; Statistics, Optimization and Information Computing, International Academic Publisher, Hong Kong and World Academy of Science, Engineering & Technology, (Scientific Committee and Editorial Board on Engineering & Physical Sciences), Italy etc. Prof. Maurya is also on role of active Fellow/Senior/Life Member of various reputed National and International professional bodies of India and abroad including Operations Research Society of India, Kolkata; Indian Society for Technical Education, New Delhi; Indian Association for Productivity, Quality & Reliability, Kolkata; Indian Society for Congress Association, Kolkata; International Indian Statistical Association, Kolkata; All India Management Association, New Delhi; Rajasthan Ganita Parishad, Ajmer and International Association of Computer Science & Information Technology, Singapore etc.

Diwinder Kaur Arora; co-author of the present paper accomplished MBA Degree with specialization in Human Resources from Pondicherry Central University, Pondicherry and she was graduated with B.Sc. (Medical/ZBC Group) Degree in 1987 from Kanpur University, Kanpur, India and did Diploma also from Government Polytechnic College, Amethi, U.P. throughout in First Division. She has vast experience of more than 22 years of general administration and management as Police Officer of Central Reserve Police Force, Ministry of Home Affairs, Govt. of India. She was selected as Assistant Sub-Inspector (Non-Gazetted Officer) in 1991 and after successful completion of her services she was promoted as Sub-Inspector in 2004 and since 2012 she is working in the grade of Inspector of Police at Group Centre, Central Reserve Police Force, Lucknow, U.P. Apart from this, she has published several research papers in Indian and Foreign International journals of repute in the field of Management, Information Technology and Physical Sciences such as in World of Sciences Journal, Engineers Press Publishing Group, Vienna, Austria; International Journal of Engineering Research and Technology, Engineering Science & Research Support Academy (ESRSA), Vadodara, India; International Journal of Electronics

Communication and Electrical Engineering, Algeria; International Journal of Information Technology & Operations Management, Academic and Scientific Publisher, New York, USA.

Er. Avadhesh Kumar Maurya; co-author of the paper accomplished his M.Tech. Degree with specialization in Digital Communication from Uttarakhand Technical University, Dehradun, UK and he was graduated with B.Tech. Degree in Electronics and Communication Engineering from Rajasthan Technical University, Kota (Rajasthan). He is recipient of four First Divisions in his Student Career with flying colours. Since last one year, Er. A. K. Maurya is serving as Assistant Professor in Department of Electronics and Communication Engineering at Lucknow Institute of Technology, U.P. Technical University, Lucknow. Prior to assuming the post of Assistant Professor at Lucknow Institute of Technology, U.P., he served as a Network Engineer for two years at Joint Venture of HCL & National Informatics Centre at Nainital, UK, India. He has worked on some projects such as Movable Target Shooter using Ultrasonic Radar and Hartley Oscillator. Apart from this, he has got industrial training in Door Darshan Kendra, Lucknow, U.P. in the field of TV Program Generation and Broadcasting of different channels for partial fulfilment of his Degree and published also several research papers in various Indian and Foreign International journals of repute in the field of Electronics & Communication Engineering, Computer Science & Information Technology and Physical Sciences such as in International Journal of Electronics Communication and Electrical Engineering, Algeria; World of Sciences Journal, Engineers Press Publishing Group, Vienna, Austria; International Journal of Information Technology & Operations Management, Academic and Scientific Publisher, New York, USA; International Journal of Engineering Research and Technology, Engineering Science & Research Support Academy (ESRSA), Vadodara, India; International Journal of Software Engineering & Computing, Serials Publications, New Delhi, India.

Ram Asrey Gautam; co-author of the present paper accomplished his M.Sc. Degree with First Division & 74% marks in Mathematics from Alagappa University, Karaikudi, Tamil Nadu in the year 2009 and he has qualified also the CSIR-NET for Lecturership in the Discipline of Mathematical Sciences in 2012. Presently he is serving as an Assistant Professor in the Department of Applied Mathematics at Lucknow Institute of Technology, Lucknow (U.P.) and also served as Sr. Lecturer for two years at GCRG Trust's Group of Institutions, Lucknow. However, he started his teaching career as Lecturer in 2009 from the Department of Applied Mathematics at Asia School of Engineering & Management, Lucknow (U.P.) and served here for one year. Besides teaching students at degree level in Technical Institute, he is actively engaged for his research in the field of both Mathematical Sciences as well as Interdisciplinary Subjects and and he has published some research papers as co-author under supervision of Prof. (Dr.) V. N. Maurya in Foreign leading International journals of Austria and USA.