Lecture Notes in Networks and Systems 1036

Jawad Rasheed
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Forthcoming Networks and Sustainability in the AIoT Era

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Contents

Analyzing the Economic Viability and Design of Solar-Powered Water Pumps for Farming Irrigation: Case Study Conducted in Somalia

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Abstract. In Somalia, livestock and agriculture are key economic sectors, heavily dependent on water resources, primarily from the Juba and Shabelle rivers used for irrigation. Traditional energy sources for irrigation are costly and require daily maintenance. Farmers distant from these rivers rely on only two rainy seasons for crop growth, However, some seasons fail to rain, and drought occurs. This study aims to evaluate the design and economics of a solar-powered photovoltaic water pumping (PVWP) system for irrigation in Somalia. A banana farm in the south served as a case study, receiving about 5.25 Kwh/m^2 of solar radiation daily. The water needs for various crops were assessed using the CROPWAT program. Crops like sugarcane, mango, and banana were found to be the most water-intensive, while sorghum, beans, and watermelon needed less water. Two PVWP system designs, AC and DC, were simulated using PVSYST software. The AC system required 6 solar panels (285wp each) to pump 82m^3/day, while the DC system achieved this with just 4 panels and greater efficiency. Economic analysis compared these systems with diesel water pumps (DWPs), using metrics like capital cost, life cycle cost, and cost per cubic meter of pumped water. The cost per cubic meter was 0.17 USD for the DC system and 0.22 USD for the AC system, significantly lower than the 0.68 USD for DWPs. The study concludes that solar photovoltaic technology can enhance agricultural productivity and food production, improving farmers' livelihoods and contributing to Somalia's economic development.

Keywords: Crop water requirement · Somalia · Photovoltaic water pumping · Photovoltaic systems

1 Introduction

When it comes to a country's development, agriculture and energy are two of the most important factors to consider. Lack of electricity is one of the biggest obstacles to the development of the remote regions in Somalia as approximately 34.7% of the population

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living in urban areas has access to electricity, while this rate is only 3.5% in the rural communities [1]. Solar energy, which is common among renewable energy sources, has the potential to provide a long-term solution to the world's energy crisis. Solar photovoltaic power is not only a solution to today's energy crisis, but it is also a green energy source [2].

Livestock and agriculture, both rain-fed and irrigated, are the Somali people's two main traditional socioeconomic pursuits, both of which rely heavily on water. Irrigation potential is 240 000 HA. The irrigation sector has seen major changes since the civil conflict began in 1991, with several large-scale irrigation installations destroyed. And, due to a lack of maintenance, the majority of the remaining infrastructure is unusable, and a large portion of the formerly irrigated land is now used for rain-fed agriculture and grazing. Agriculture is primarily irrigated along the Juba and Shabelle rivers. Farmers along these two rivers use conventional energy sources such as diesel pumping systems to irrigate their farms. These types of systems require a constant high fuel cost and daily maintenance and very few of them can afford it. Farmers far from the river, on the other hand, have to leave only two rainy seasons a year to grow their crops. As a result, the absence of rains and droughts throughout the growing season has frequently resulted in serious food shortages and animal losses [3–5].

Solar photovoltaic panels are being used in a variety of applications to power heating systems and meet domestic loads in both rural and urban areas. Other applications include street lighting, battery charging, rural health center vaccine refrigeration, satellite power systems, and emergency communication applications. Pumping water is one of the most essential uses for photovoltaic systems, especially in rural locations that receive a lot of solar radiation and don't have a connection to the national grid. Solar water pumping systems have become increasingly popular in recent years as the cost of photovoltaic modules has decreased substantially [2, 6].

In the current energy crisis in Somalia, a solar photovoltaic irrigation system could be a realistic choice for farmers. A solar pump runs on electricity provided by photovoltaic panels. Solar pumps are more cost-effective due to lower operating and maintenance expenses, as well as having a lesser impact on the environment than pumps driven by internal combustion engines [7].

Many research studies show that some of the renewable energies, Especially Solar energy, can be economically more suitable for pumping systems compared to diesel generators. Authors in [8] and [9] conducted two similar studies on evaluating the economic and financial assessment of different sizes of solar and diesel engine pumps. To calculate the overall economic viability of solar irrigation, authors included other elements, like hydraulic demands, irradiation, pump heads, interest rates, PV costs, and fuel costs. When interest rates for equal plant size for solar PVs and diesel pumping were set from 0 percent to 20 percent, photovoltaic Solar pumping proved to become a more viable option than diesel pumps.

Also, authors in [10] conducted a study on solar Photovoltaic pumping systems in distant places to analyze the technological and financial factors. The findings show that in distant places where the grid energy is unavailable, solar PV pumping is a perfect alternative. Furthermore, water availability provides major benefits to the socio-economic and physical well-being of rural farmers.

On the other hand, a research study in [11] compared diesel engine pump systems to PV water pumping systems for distant locations in his research study. Using both an analysis of cost and value, he compared the current value of diesel and solar pump systems. The objective was to design the greatest cost-effective pumping system possible for a given hydraulic capacity. The findings demonstrate that diesel and PV pump systems' pumping costs per cubic meter of water are $0.58 and $0.20, respectively. In cases when grid-lines aren't accessible, Photovoltaic pumping systems are much more cost-effective than diesel pumps. Solar irradiation, Photovoltaic array size, pumping level, agricultural patterns, and whether the water pump is AC or DC are all factors to consider when designing and building an accurate photovoltaic water pumping system. The proper sizing of a PV pumping system for irrigation maximizes electricity production, improves system efficiency, and lowers total costs [12].

In this study, a district called Afgooye in Southern Somalia was taken as a case study. The reasons behind choosing this region are due to its high solar potential, enormous agricultural activities, and abundant water resources. Using the CROPWAT program, the irrigation water requirement of some common crops cultivated in the district was calculated. In addition, the crops that use the least and most water in terms of annual water consumption were identified. Then, based on the value of the daily water requirement for bananas, two configurations (AC and DC) of solar water pumping systems were designed. PVsyst software was used to design and simulate both solar water pumping systems. In addition, the study compared and evaluated three systems: AC solar water pumping, DC solar water pumping, and diesel pumping systems. Capital costs (CC), life cycle cost (LCC), and m^3 cost of pumped water were all used to do the comparison. The project was viewed not only in terms of an economic perspective but also in terms of an environmental perspective. An environmental advantage of PVWPs used instead of DWPs was evaluated using CO_2 emission reduction.

2 Solar Energy Potential in Afgooye

Due to its geographical location and climatic characteristics, all Somali regions have significant potential in terms of renewable and alternative energy sources, such as solar and wind energy. Somalia has been granted high and stable solar radiation throughout the country. The average solar energy potential is at the level of 5–7 $kWh/m^2/day$. With over 3,000 h of high and constant sunlight a year, Somalia is in an ideal location to use solar energy [13].

In this paper, a farm located in the Afgooye district was taken as a case study. Afgooye is a town in the southern Somalia Lower Shebelle region of Somalia. It is 30 km north of the capital, Mogadishu. The Shabelle River passes through the middle of the town. Its location is at an altitude of 83m above sea level at 2.1381 north latitude and 45.1312 east longitude. Information on average monthly solar radiation at the selected site was found using PVsyst software. There are three different databases in PVsyst software; PVGIS (Photovoltaic Geographic Information System), Meteonorm, and the National Aeronautics and Space Administration (NASA). Table 1 illustrates the monthly averaged solar radiation data from the PVsyst software's various databases, as well as the temperature for Afgooye.

Table 1. Monthly average solar radiation potential and temperature in Afgooye.

Month	Global horizontal irradiation (Kwh/m^2/day)			
	PVGIS	NASA data	Meteonorm data	Temperature (°C)
Jan	6.79	6.09	5.67	28.5
Feb	7.46	6.63	5.72	29.6
March	7.52	6.55	5.58	30.3
Apr	6.95	5.75	5.47	29.2
May	6.26	5.44	5.17	28.6
Jun	6.11	5.08	4.71	26.6
Jul	5.46	5.00	4.59	26.5
Aug	6.15	5.41	4.75	26.4
Sep	7.00	5.80	5.36	27.0
Oct	6.84	5.39	5.16	28.6
Nov	6.50	5.31	5.33	27.9
Dec	6.39	5.51	5.54	28.3
Average	**6.61**	**5.66**	**5.25**	**28.1**

Meteonorm is considered a more reliable source of meteorological data, with less uncertainty associated with global horizontal irradiation than the other two data sources [14]. To see the chart, PVGIS, NASA, and Meteonorm data of Afgooye's monthly average solar irradiation are graphically displayed in Fig. 1. Meteonorm data were used to simulate the project. According to Meteonorm data, the field receives good solar irradiation, with monthly averages ranging from 4.59 kWh/m^2 in the lowest months to 5.72 kWh/m^2 in the highest months, and an annual average of 5.25 kWh/m^2/day.

3 Irrigation Water Requirement

Calculating the irrigation water requirements is the first stage in designing a Photovoltaic pumping system. The irrigation water requirements of some common crops grown in the district were calculated in this study using the CROPWAT software. In addition, the crops that use the least and most water in terms of annual water use were identified. In the study area, agricultural products like maize, sorghum, cowpea, sesame, tomato fruits (banana, Sugarcane lemon, and other citrus fruits, guava, mango, papaya, watermelon, and dates), and vegetables are widely grown. Using the CROPWAT program, the net irrigation requirement and gross irrigation requirement of some of these crops were calculated individually. The amount of water needed for crop growth is known as the net irrigation water requirement (NIWR). The gross irrigation water requirement (GIWR) is the amount of water that should be applied in reality after water losses are taken into account. Table 2 shows the Net irrigation requirement and gross irrigation requirement of some crops common in the Afgooye region.

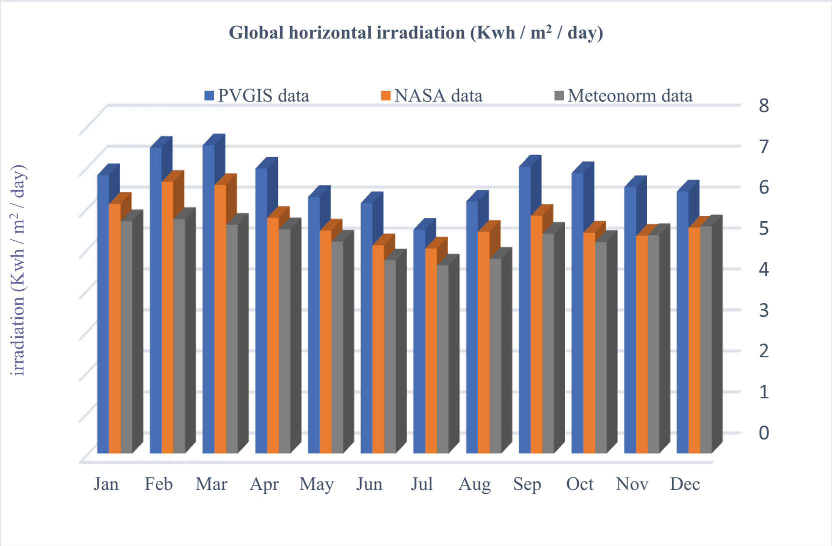

Fig. 1. Monthly solar irradiation potential in Afgooye

Table 2. Net and gross irrigation requirements of some crops common in the Afgooye district.

Crop	NIWR (mm)	GIWR (mm)
Maize	470	671.4
Sorghum	413.2	590.3
Beans	456.2	651.7
Patato	518.7	741.0
Tomato	465.9	665.5
Citrus	612.2	874.6
Ground nut	486.6	695.1
Sugarcane	1152.7	1646.7
Banana	1043.3	1490.5
Mango	1054.7	1506.7
Watermelon	404.8	578.6
Vegetables	481.2	687.4

The gross irrigation water requirement for bananas calculated and simulated by the CROPWAT program is 1490.5 mm/year. 1mm corresponds to 10m^3 / hectare, therefore:

$$\text{IWR} = \frac{1490.5\text{mm}}{365 days} \times \frac{10\frac{m^3}{ha}}{1mm} = 41\text{m}^3/\text{day/ha} \tag{1}$$

Using the CROPWAT program, the daily irrigation water requirement for a two-hectare banana farm is 2x41 m^3/day = 82 m^3/day. As a result, the system is designed to meet 82 m^3 of water per day. Also, the storage tank was designed or sized for a four-day capacity, therefore: Water storage volume = 82 m^3 / day * 4 days = 328 m^3.

4 Design and Simulation of PV Pumping in Pvsyst Software

In this study, PVsyst software is used to design and simulate two configurations of solar PV water pumping systems. The geographical location of the project, crop water needs, and the tilt angle under which the PV modules should be installed to optimally convert available solar irradiation into electric power are the most important input parameters in PVsyst when designing and simulating a PVWP with tank storage. The location of the project is Afgooye and the meteo data used for the simulation was collected from the Metronome 7.1 through the Pvsyst software. The irrigation water requirement of two hectares of banana farms was calculated using the CROPWAT program and found to be 82m3/day. Both AC and DC pumping systems will be designed to meet the same farm's irrigation requirements. The PV models, both AC and DC pumps, and all other required materials are selected from the database of the PVsyst program according to the maximum possible annual needs.

4.1 Simulation Results of DC Water Pumping

According to the simulated results, the yearly water consumption for the banana plantation is 29930 m^3, whereas the pumping system can deliver about 30070 m^3, resulting in missing water (needed water not pumped) of about 0.5 percent. The amount of water that is missed is calculated as follows:

$$\text{Missing water } (\%) = ((29930 - 30070)/30070) \times 100 = -0.4655 \approx -0.5\%$$

Table 3 displays the monthly distribution of pumped water and missed water, along with other factors. The aim is to decide the month that banana trees need a critical minimum effective supply of water. Starting with solar radiation and concluding with water production, the system loss diagram (see Fig. 2) illustrates all minor and major losses. By defining the major factors that cause losses, the loss diagram gives a convenient and insightful look at the quality of a PV system design. The loss diagram can be shown for the entire year or for each month to assess the seasonal impact of specific losses. The overall system loss diagram for the designed system is shown in Fig. 2.

According to the loss diagram, on the horizontal plane, the average annual solar radiation is 1916 kWh/m^2. On the collector plane, the effective irradiation is 1846 kWh/m^2. The Photovoltaic system then transforms the solar energy into electricity. The nominal energy of the array after PV conversion is 2119 kWh. At Standard Test Conditions, the PV array's efficiency is 14.78% (STC). The virtual energy generated from the array is 1793 kWh. The available energy at the output after the electrical loss is 1667 kWh. The pump utilizes 1331 kWh of operating electrical energy and 580 kWh of hydraulic energy. The annual pumped water volume is 30070m^3, and it is greater than the user's water need. As a result, the designed system is capable of irrigating two hectares of banana farms.

Table 3. The monthly distribution of the pumped water and the missing water.

	GlobEff kWh/m^2	EArrMPP kWh	E PmpOp kWh	ETkFull kWh	H_Pump meterW	WPumped m^3/day	W Used m^3/day	W Miss m^3/day
Jan	187.3	178.6	123.2	41.78	7,071	86.62	82	0
Feb	164.2	156.1	104.1	40.11	7,066	81.98	82	0
Mar	168.1	159.5	110.9	35.08	7,060	79.98	82	0
Apr	149.8	145.3	110.1	25.15	7	83.13	82	0
May	138.9	136.9	108.5	19.46	7,052	80.72	82	0
Jun	120.4	120.7	105.5	7.41	7,045	82.7	82	0
Jul	122.8	122.9	107.7	7.19	7,047	81.28	82	0
Aug	132.2	131.6	112.9	10.36	7	84.22	82	0
Sep	151.8	148	109.6	28.47	7,057	81.96	82	0
Oct	159.3	153.9	112.1	30.52	7	81.58	82	0
Nov	167.1	162	111.1	40.3	7,063	82.43	82	0
Dec	184.4	177.7	115.8	49.92	7	82	82	0
Year	1846.4	1793.1	1331.5	335.73	7	82.38	82	0

4.2 Simulation Results of AC Water Pumping

PVsyst software was also used in this case study to model an AC water pumping system, which is another configuration of solar photovoltaic water pumping system. The primary input parameters (geographical and metrological data, definition of the user's water needs, characterization of the storage tank, plane orientation, and photovoltaic system) to design and simulate for both configurations of PVWPs are all the same, except that the first configuration uses a DC pump and a DC/DC converter, while the second configuration uses an AC pump and a DC/AC inverter. In the case of an AC PV-powered water pump, the yearly water consumption for the banana plantation is 29930 m^3, whereas the pumping system can deliver about 30070m^3, resulting in missing water (needed water not pumped) of about 0.5 percent, according to the simulated results. The same result as DC water pumping. Table 4 displays the monthly distribution of pumped water and missed water, along with other factors.

Using the Pvsyst program, two configurations were designed and simulated: AC photovoltaic water pumping and DC photovoltaic water pumping, both with storage tanks. The two solar photovoltaic system configurations were planned to irrigate two hectares of a banana farm. According to the simulation results, in the case of DC pumping, four solar panels are used to pump the amount of water required, which is 82 m^3/day, while six panels are used to produce the same quantity of water in the AC system. The efficiency of the DC system is also higher than the AC system, according to the simulation results.

5 Economic Evaluation and Environmental Analysis

In this section, the cost comparisons between the AC and DC pumping systems were conducted and the economic evaluation for both configurations of PVWP systems was compared with diesel water pumping. The comparison was made according to capital costs, life cycle cost, and m^3 cost of pumped water. In terms of environmental analysis, CO2 emission reduction was evaluated using DWPs in place of PVWPs.

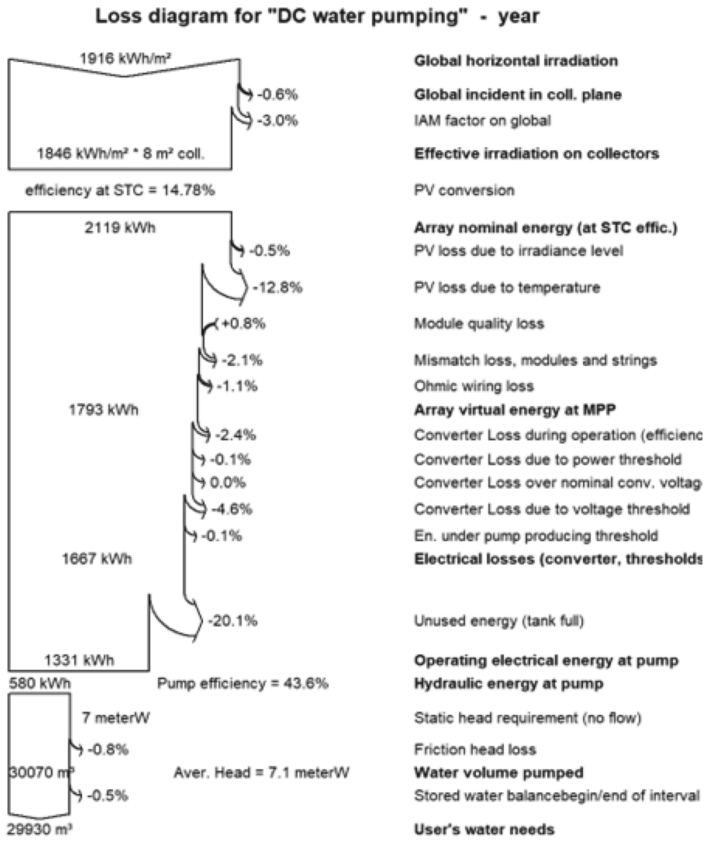

Fig. 2. The loss diagram of the DC solar pumping system

The following are some of the major assumptions used in economic assessments of PVWPs [15] [16]: PV panels were expected to have a 20-year operating life. The life of an AC solar pump was estimated to be 8 years and that of a DC solar pump to be 10 years. The annual maintenance expense for both PV systems is estimated to be 0.1 percent of the overall capital cost. The salvage value of a PV system is 15% of the overall purchase price. A diesel engine's salvage cost was considered to be 20% of the engine's capital cost. The annual availability of sunshine hours is estimated to be 3000 h. It was assumed that the discount rate would be 10%. In Somalia, the cost per watt peak

Table 4. The monthly distribution of the pumped water and the missing water.

	GlobEff kWh/m^2	EArrMPP kWh	E PmpOp kWh	ETkFull kWh	H_Pump meterW	WPumped m^3/day	W Used m^3/day	W Miss m^3/day
Jan	187.3	267.8	172.3	85.49	7.084	86.61	82	0
Feb	164.2	234.2	145	80.34	7,077	81.97	82	0
Mar	168.1	239.2	157.5	71.69	7.07	81.21	82	0
Apr	149.8	218	152.5	55.59	7,066	82.76	82	0
May	138.9	205.3	147	48.31	7.064	79.63	82	0
Jun	120.4	181	148.5	22.44	7,060	84.4	82	0
Jul	122.8	184.4	145.2	29.59	7,056	80.08	82	0
Aug	132.2	197.4	154.3	33.69	7,060	83.97	82	0
Sep	151.8	222	153.3	58.98	7.068	82	82	0
Oct	159.3	230.8	155.3	65.96	7,066	81.81	82	0
Nov	167.1	243.1	152.6	81.33	7.073	82.2	82	0
Dec	184.4	266.5	159.3	97.18	7,083	82	82	0
Year	1846.4	2689.6	1842.7	730.6	7,068	82.38	82	0

of the solar module is $0.6. According to the simulated results, AC pumps require more solar panels than DC pumps. Therefore, AC water pumping is expected to cost $5006 in initial capital and installation costs, while DC water pumping would cost $4204. Solar modules with a capacity of 285 watts, mounting brackets, pump controllers, inverters, DC and AC pumps, storage tanks, other components, installation, and transportation are all considered. Some major assumptions used in economic assessments of Diesel Water Pumping systems are as follows [15]: It was supposed that the pump runs for 5 h a day, has a 60% efficiency, and needs to be replaced after 10 years. The same 10 percent discount rate as for PVWPs has been considered. It was also estimated that the annual operating cost for a diesel pump is 10% of the capital cost and that the salvage value of a diesel engine is 20% of the capital cost. The cost of a 3-horsepower diesel engine, including its components, is $2500, and it uses 0.6 L of diesel per kW. In Somalia, the price of diesel fuel is currently 0.5 dollars per liter.

$$\begin{aligned} &\mathit{Annual\ Fuel\ Cost} \\ &= \mathit{Specific\ Fuel\ Consumption} \\ &\times \mathit{Total\ Operating\ Hours\ in\ a\ Year} \times \mathit{Fuel\ rate} \\ &= 0.6\mathit{litres/hr} \times (5\mathit{hr/day} \times 365\mathit{day/year}) \times \$0.5/\mathit{liter} = \$547.5/\mathit{year} \\ &\mathit{Fuel\ Cost\ ofDieselGeneretorfor}20\mathit{years} = 20\mathit{Year} * \$547.5/\mathit{year} \\ &= \$10950 \end{aligned} \tag{2}$$

The study compares the costs of the three systems, AC solar pumping, DC solar pumping, and diesel pumping systems for the Afgooye site, using the life cycle cost analysis approach. The method of assessing a project's economic performance throughout its expected lifetime is known as life cycle cost analysis. MS Excel was used to calculate the life cycle cost evaluation. The following formula can be used to compute the life-cycle cost:

$$LCC = CC + MC + EC + RC + SC \tag{3}$$

where CC is capital cost, MC is maintenance cost, EC is the Energy cost per fuel cost, RC is the replacement cost, and SC refers to salvage cost. Both AC and DC water pumping systems, as shown in Fig. 3, have higher capital costs than diesel water pumping.

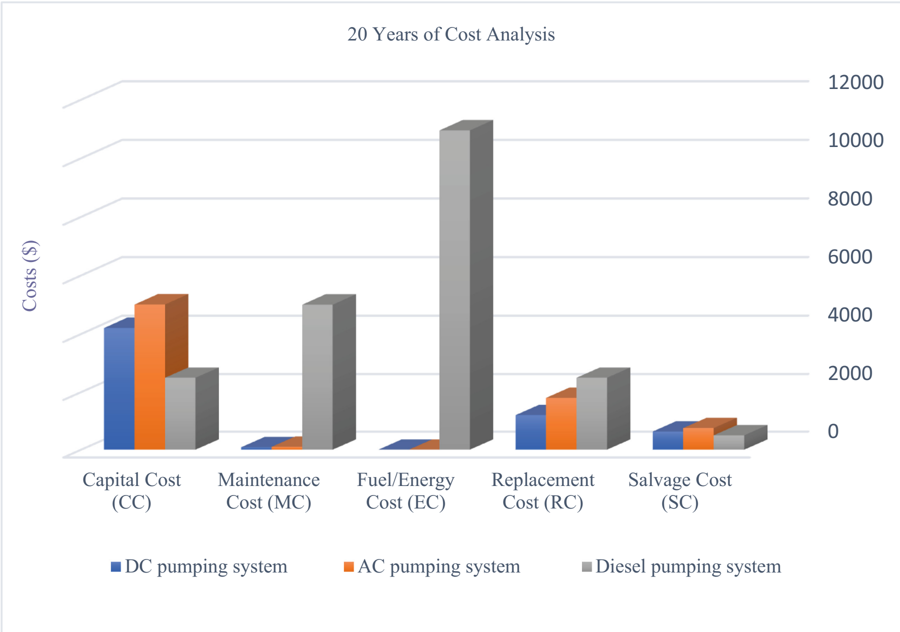

Fig. 3. Comparison of life cycle costs for all three systems.

The operating and maintenance costs, as well as fuel costs, are higher for the diesel system, according to the calculation of the life cycle costs of both systems. Any system designed to pump water has a substantial effect on the life cycle cost analysis. Based on the power source, apart from the sun, which is a free source of energy, diesel is more expensive, and these numbers may continue to rise if fuel costs continue to rise.

Figure 4 shows the capital cost and life cycle cost for both systems throughout a 20-year life cycle. The costs per m^3 of pumped water were also considered in the economic study of the three systems.

PVsyst software was used to evaluate both AC and DC photovoltaic pumping systems. Table 5 shows an overview of the cost per m^3 of pumped water for the two configurations. To prove the feasibility of both PV pumping systems, the cost per m^3 of pumped

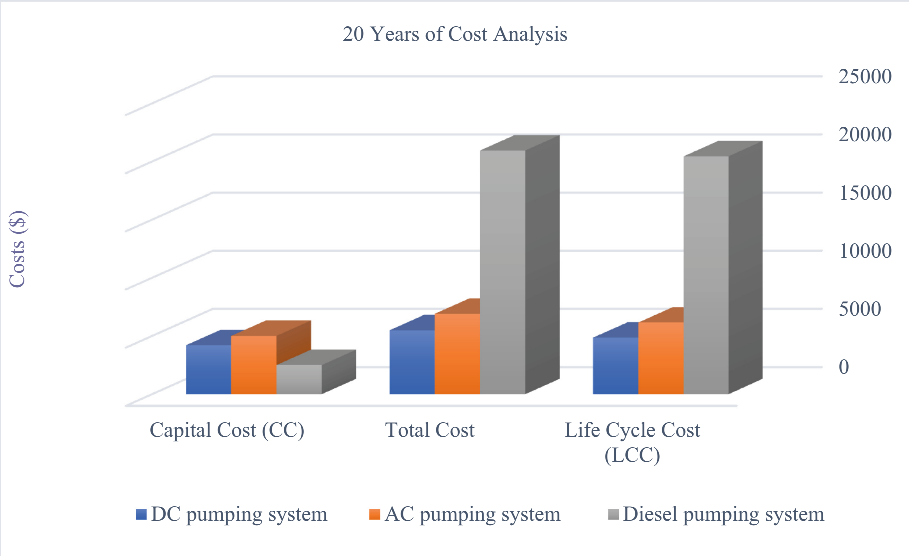

Fig. 4. Capital costs, Total cost, and Life Cycle for 20 years

water by a diesel pumping system is calculated using the cost annuity methodology based on the life-cycle evaluation [17].

$$\textit{Cost of } m^3 \textit{ of water pumped} = \frac{\textit{Annualised life cycle cost of the system}}{\textit{Total pumped water}} \quad (4)$$

Since the total annual water pumped is 30070 m^3/year and the annualized life cycle cost for the Diesel pumping system is \$20450, the water cost for the Diesel pumping system is 0.68 USD/m^3.

Table 5. Overview of the cost per m^3 of pumped water used for the two configurations.

Water and Energy costs	DC water pumping system	AC water pumping system
Total installation cost	4′204.00 USD	5′006.00 USD
Operating costs	84.08 USD/year	100.12 USD/year
Water Pumped	30070 m^3	30070 m^3
Cost of pumped water	0.17 USD/m^3	0.22 USD/m^3

In terms of environmental impact, according to https://www.worldometers.info, Fossil CO_2 emissions in Somalia were 1,268,442 tons in 2016. When many farmers become familiar with the use of photovoltaic technology in agriculture, the amount of CO_2 emissions saved by PVWPs will contribute to an annual reduction in Greenhouse gas emissions. CO_2 emission reduction was evaluated using DWPs in place of PVWPs.

According to the results from HOMER software, using photovoltaic water pumping systems in place of Diesel water pumping will contribute to an annual reduction of CO_2 emission by 2597 kg.

6 Conclusions

The primary objective of this study was to concentrate on the design and cost assessment of a photovoltaic pumping system in Somalia. A banana plantation situated in southern Somalia was selected as a subject of investigation. The site experiences a daily horizontal solar radiation exceeding 5.25 Kwh/m^2, which is highly promising for the utilization of solar Photovoltaic technology. The CROPWAT program was utilized to compute the irrigation water demand for various commonly grown crops in the area. Furthermore, an analysis was conducted to determine the crops with the lowest and highest water consumption, measured in terms of annual water consumption. Based on the simulated data, Sugarcane, mango, and banana were found to be the crops that required the most water, while sorghum, beans, and watermelon were identified as the crops that required the least amount of water. The PVSyst software was used to design and simulate two types of photovoltaic water pumping systems: AC and DC configurations. In the case of AC pumping, the simulation results indicate that 6 solar panels, each with a power output of 285wp, are used to pump 82m^3 of water per day. On the other hand, the DC system achieves the same water output with higher efficiency using only 4 panels. The economic evaluation of the two configurations of PVWP systems was conducted by comparing them to DWPs. The comparison was conducted using capital costs (CC), life cycle cost (LCC), and the cost per cubic meter of pumped water. The total projected expenses for the two designed configurations, namely the DC water pumping system and the AC water pumping system, amount to $4204 and $5006, respectively. The annual cost for the DC system is estimated to be $84.08, assuming a service lifetime of 20 years. The cost for the case AC system is $100.12. The life-cycle costs of the diesel pumping system amounted to $20,450. The cost of water in the DC system is 0.17 USD/m^3, while in the AC system, it is 0.22 USD/m^3, calculated based on the projected lifespan of the power generation system. Both instances of photovoltaic pumping systems are more financially advantageous than DWPs, where the water's equivalent cost is 0.68 USD/m^3. Consequently, the implementation of solar photovoltaic technology has the potential to greatly enhance agricultural productivity and food production. This, in turn, would elevate the living standards of farmers and make a substantial contribution to the economic growth of the country.

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Evaluation of No-Load Losses in the Single-Sheet, Double-Sheet, and Triple-Sheet Step Lap Joints of the Transformer Core

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Abstract. Power transformers are crucial pieces of equipment in power grids, and the working of transformers directly impacts the safety of the power system. Transformer-increased losses due to core design can increase the transformer's operational cost. With the development of numerical methods and the growth of finite element analysis techniques, tremendous progress has been made in applying the finite element method in the design of the transformer, which provides new ideas for designing and optimizing the transformer design. This paper analyzes the no-load losses of step lap cores based on finite element analysis and summarizes the impact of flux density distribution on single-sheet step lap joints (SSSL), double-sheet step lap joints (DSSL), and triple-sheet step lap joints (TSSL). Three different step lap joints of power transformers are examined at different magnetic flux densities and give guidelines to select the optimal step joints to achieve low losses and cost-effective design.

Keywords: Core, Double-sheet Step Lap Joints · Finite Element Analysis · Single-sheet Step Lap Joints · Transformer, Triple-sheet Step Lap Joints

1 Introduction

Transformers are the most expensive and crucial parts of power systems that aid in the efficient and reliable transmission and distribution of electricity. To ensure reliable electricity distribution, transformers must be designed properly. The core composition of power transformers remains almost unchanged; the manufacturing of the core is influenced by several factors such as core type, core material, and type of joints [1].

No-load losses may cost more than the overall cost of the transformer, depending on the operation and life of the transformer. The two main aims of the transformer designers are to

- Minimize the total no-load losses.
- Appropriately calculate the no-load losses during the initial design stage of the transformer.

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Customers generally ask for the minimum no-load losses, due to which minimizing the losses is one of the crucial factors while making the core of the transformer. Another important parameter during the design of the core is to calculate the no-load losses accurately; transformer designers have to pay heavy fines and penalties if the guaranteed no-load losses and experimental no-load losses vary significantly (more than 10%) or sometimes the transformer designer has to supply the maximum total no-load losses and losses must be under maximum supplied no-load losses.

In order to attain the desired performance of low noise levels, low exciting power, and losses; more attention must be placed on cores that have high magnetic induction, low coercivity, and high permeability.

Studies have shown that silicon steel cores have lower magnetic flux density levels in step lap joints compared to conventional joints, resulting in lower no-load losses.

[2] studies the impact of various multiple step-lap connections on magnetic induction. [2] suggests that a change in the step numbers will enable silicon steel cores to behave according to the requirement (minimal noise and core losses). Evaluation of the equivalent magnetic properties for the constructed structure in the anisotropic lamination sheets is studied in [3]. Acoustic noise in the cores also results from changing magnetostrictions [4]. A novel step-lap design is created in [5] to reduce noise, no-load loss, and exciting power. The butt lap step can also be used to reduce the magnetic flux changes in the amorphous core step transformer [6].

The finite element analysis is also used in [7, 8] to analyze various step-lap joints in the three-phase transformer. The [7, 8] claim that employing a T-Joint wound core can result in low core losses and exciting current.

The magnetic flux density distribution of the transformer also provides information about thermal behavior. The effect of the step lap joints on the no-load losses at different magnetic flux densities is typically assessed by a no-load test, which is a challenging task. A finite element analysis technique for the transformer's step lap no-load loss based on the numerical method is presented in this paper.

This paper illustrates how magnetic flux densities affect the no-load losses in three different step lap joints with three-layer units. This work summarizes the effects of flux density distribution on traditional single-sheet step lap joints (SSSL), double-sheet step lap joints (DSSL), and triple-sheet step lap joints (TSSL) and analyses the no-load losses of step lap cores using finite element modeling.

2 Design and Simulation Results of SSSL, DSSL, and TSSL

In an electric power system, transformers are a critical part. The designing and optimization of transformers using finite element analysis have advanced significantly in recent years due to the significant growth of the numerical method. When applied to electrical machines, finite element analysis has even surpassed the accuracy of traditional analytical methods. Research on the optimization and modeling of the transformer using finite element analysis has increased significantly and has achieved higher accuracy than traditional methods based on analytical methods [9, 10].

The finite element analysis method is a useful technique to evaluate the no-load losses at the different magnetic flux densities on the different step-lap joints. The paper examines magnetic flux densities' impact on no-load losses in step lap joints using traditional single-sheet step lap joints and other two-step-lap joints i.e., double-sheet step lap joints, and triple-sheet step lap joints.

Step-lap geometries of the SSSL, DSSL, and TSSL are shown in Figs. 1, 2, and 3.

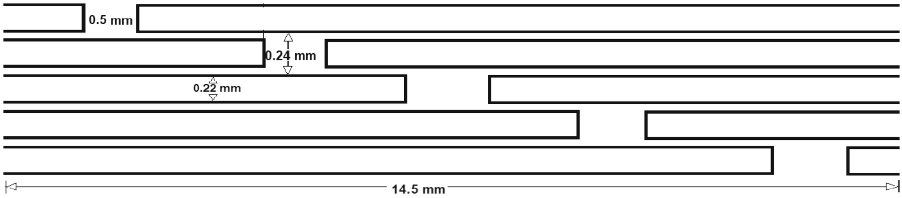

Fig. 1. Step-lap geometry of SSSL.

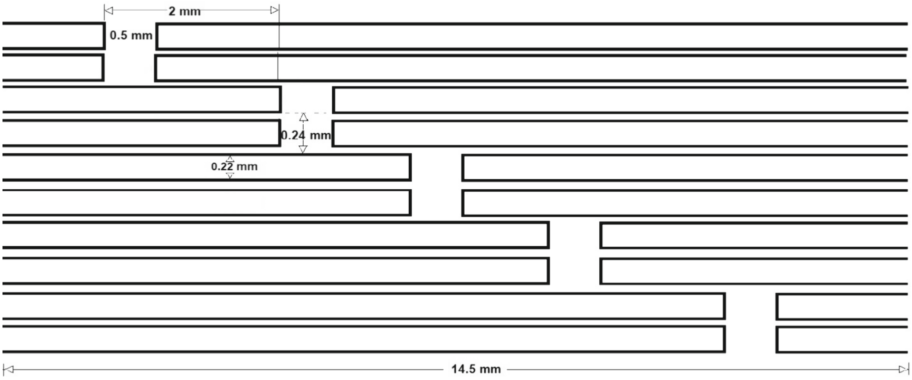

Fig. 2. Step-lap geometry of DSSL.

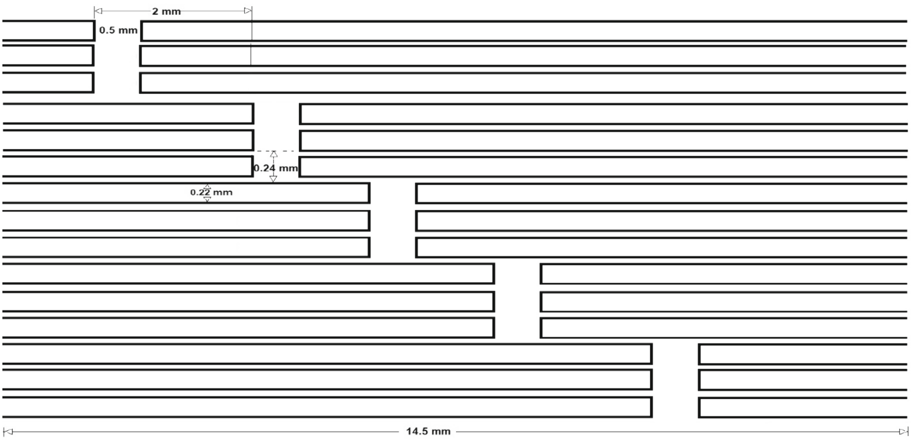

Fig. 3. Step-lap geometry of TSSL.

Mesh operation of the SSSL, DSSL, and TSSL are shown in Figs. 4, 5, and 6.

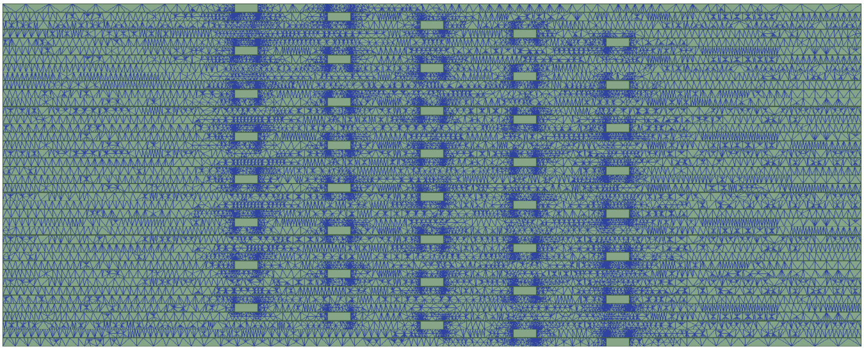

Fig. 4. Mesh operation of SSSL.

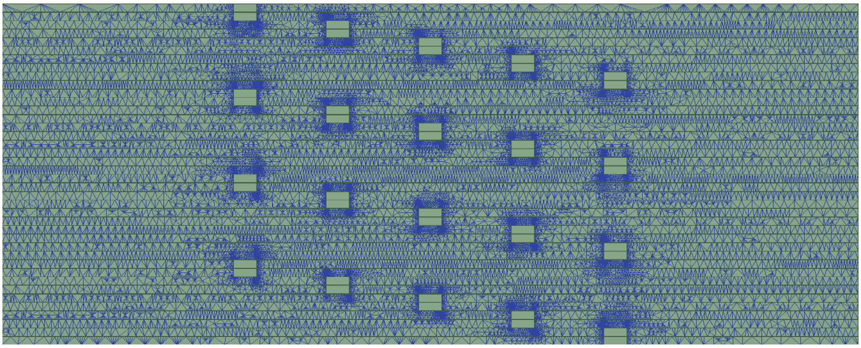

Fig. 5. Mesh operation of DSSL.

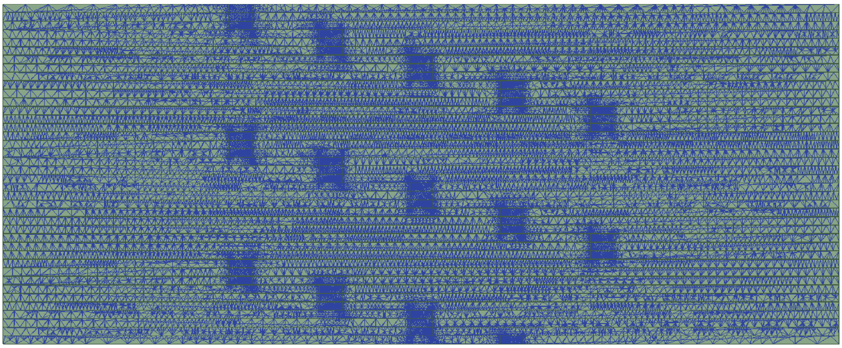

Fig. 6. Mesh operation of TSSL.

The core was designed using M-4 cold-rolled grain-oriented steel. Simulations are carried out at 50 Hz. 8 layers are used for the SSSL and 4 layers are used for the DSSL to make an equal cross-section area for both setups. A similar cross-sectional area was also used for the TSSL.

Figures 7, 8, 9 and 10 show the magnetic flux density distribution in SSSL at 0.5 T, 1 T, 1.5 T, and 2 T.

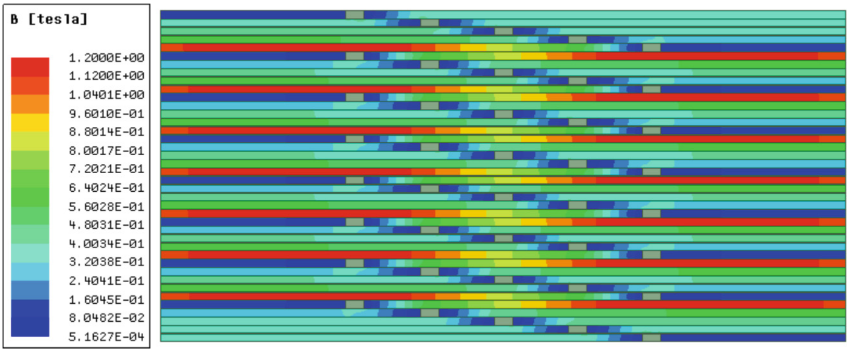

Fig. 7. Magnetic flux density distribution in SSSL at 0.5 T.

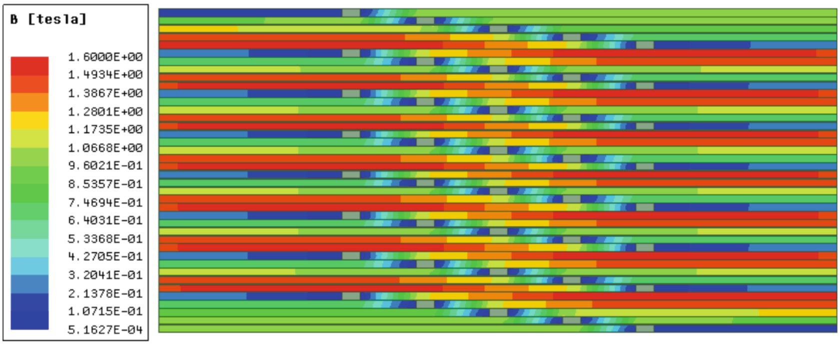

Fig. 8. Magnetic flux density distribution in SSSL at 1 T.

Figures 11, 12, 13 and 14 show the distribution of the magnetic flux density in DSSL.

Figures 15, 16, 17 and 18 show the magnetic flux density distribution in TSSL at 0.5 T, 1 T, 1.5 T, and 2 T.

The simulations are performed from 0.05 T to 2 T with an interval of 0.05 T. Table 1 shows some of the no-load losses (in watt) simulation results.

The simulation results of core losses based on the SSSL, DSSL, and TSSL are displayed in Fig. 19.

The results show that the losses are less in the SSSL as compared to the DSSL and TSSL joints. No-load losses are approximately 22.2% less in SSSL as compared to the DSSL at 0.1 T. No-load losses are approximately 8.7% less in SSSL as compared to the DSSL at 1 T. No-load losses are approximately 0.5% less in SSSL as compared to the DSSL at 2 T. No-load losses are approximately 49.2% less in SSSL as compared to the

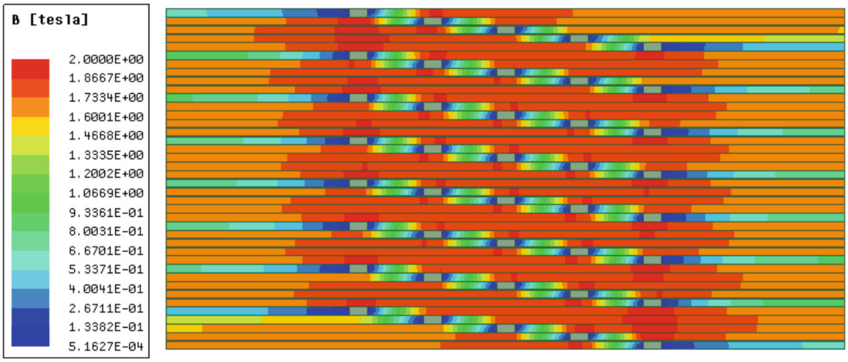

Fig. 9. Magnetic flux density distribution in SSSL at 1.5 T.

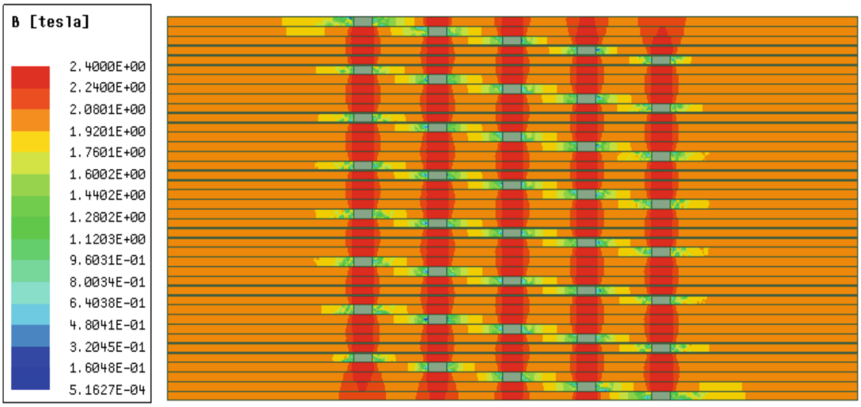

Fig. 10. Magnetic flux density distribution in SSSL at 2 T.

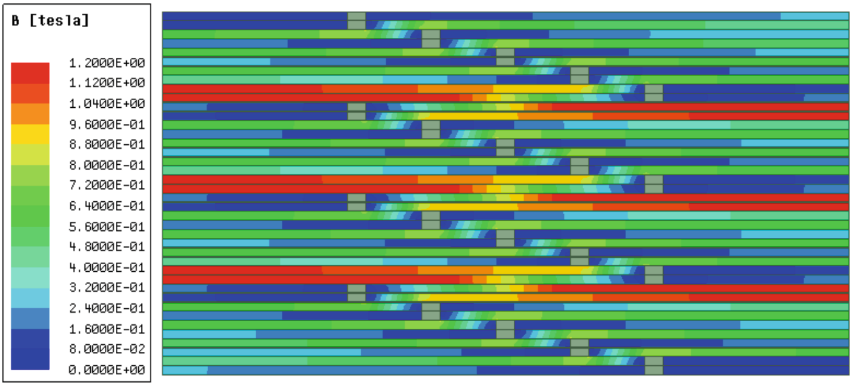

Fig. 11. Magnetic flux density distribution in DSSL at 0.5 T.

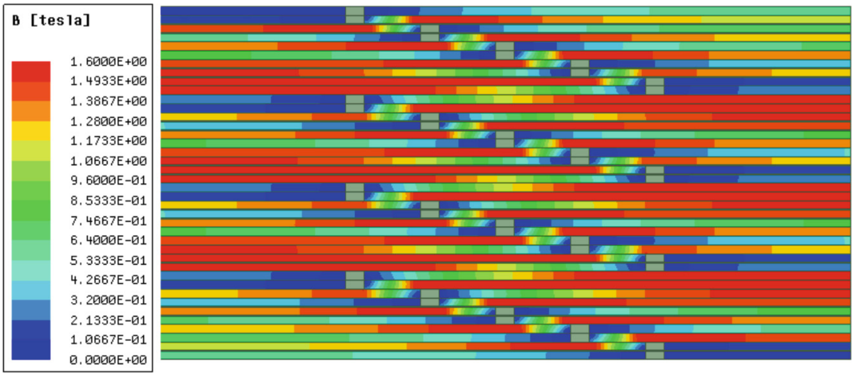

Fig. 12. Magnetic flux density distribution in DSSL at 1 T.

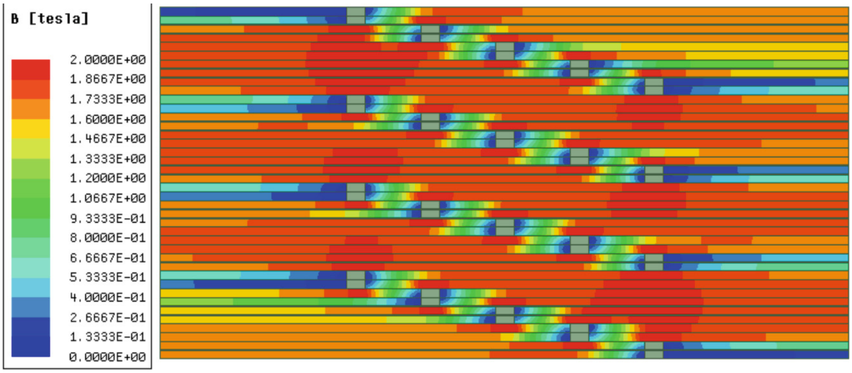

Fig. 13. Magnetic flux density distribution in DSSL at 1.5 T.

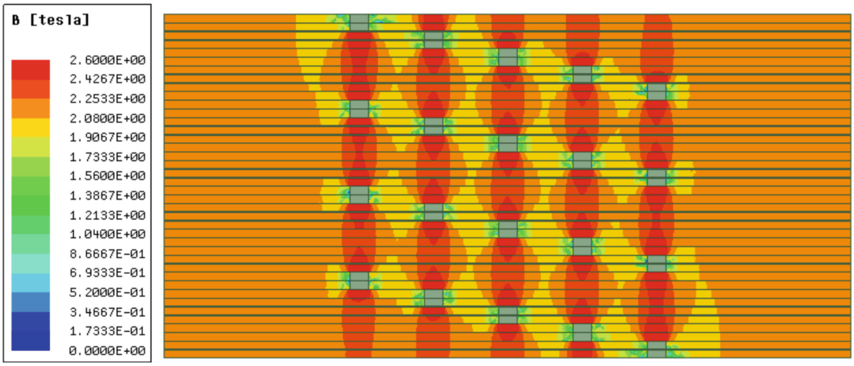

Fig. 14. Magnetic flux density distribution in DSSL at 2 T.

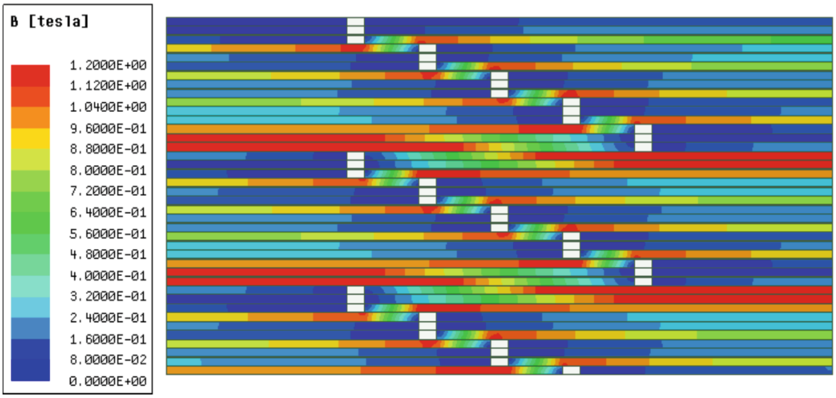

Fig. 15. Magnetic flux density distribution in TSSL at 0.5 T.

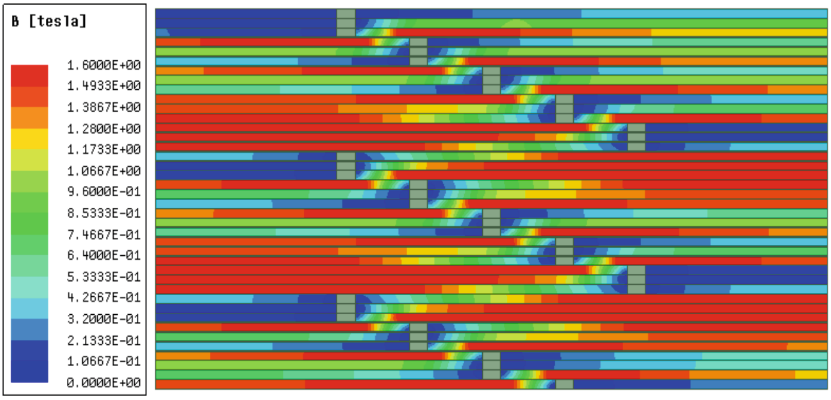

Fig. 16. Magnetic flux density distribution in TSSL at 1 T.

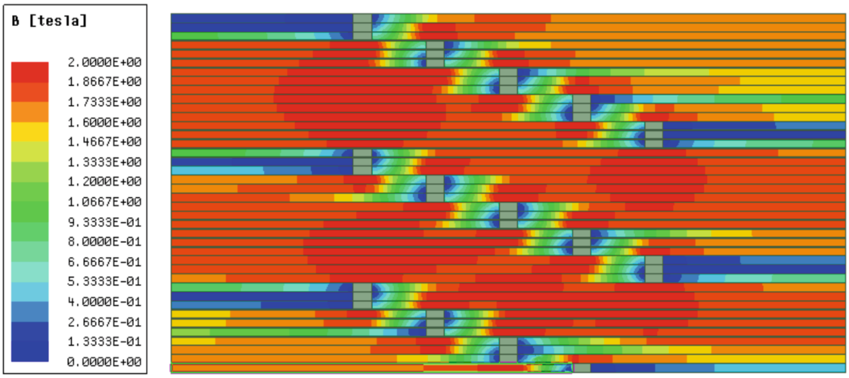

Fig. 17. Magnetic flux density distribution in TSSL at 1.5 T.