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Design and development of bullock drawn mobile solar operated water lifting system

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Abstract
This paper presents design and development of bullock Mobile Solar operated water lifting System. The experimental setup is built up in UAE, CAET, Parbhani Maharashtra, India. Solar power generating system performs operation of water pumping. Solar power generating system is designed with main frame attached with solar panel carrier, and variable frequency drive. Pneumatic tyres are use to transport system on and off the road to reduce animal drudgery. 9 panel of 335 watt each are connected in series to obtained 3 Kw power to run 3-phase AC motor to lift water. 3 kW Mobile solar operated water pumping system is designed for remote location where electric facility is not available so that farmers can irrigate farm in day time. Solar water pumping is mainly depending on two parameters ground water potential and solar radiation has been recorded for different time of day span. In normal sunny days average radiation (410 W/m^2) motor output was found optimum (1440 RPM) for 5 hr.in one day. Hence motor can be very well operated for five hours in a day. Discharge in the range of 90.9 to 33.3 lpm for the solar insolation ranging between 455 to 92 W/m^2. Solar power generating system is more appropriate for water pumping due to its operational cost, low maintenance cost over diesel pump especially for remote area.

Keywords: Solar water lifting, CAET, 3- Phase, solar radiation

Introduction

Energy is an important element in development process. Energy issue is a global concern, given the recurrent crises in the electricity sector. During the last decade, the energy sectors of many countries bear severe changes with stimulus to the decentralization of power generation, giving the distribution network a central role in new model. Energy generation plays a lead role in human life, along with means of transportation, telecommunications, water and sanitation. However, both the use and generation of energy should be handled in a harmonious way and appropriate to the environment, so that natural resources can be used rationally and viably. India has a vast supply of renewable energy resources. India is blessed with high level of solar radiations with high level of 4-7 kWh/m^2/day and 1200-2300 kWh/m^2/year, and it has one of the largest programs in world for deploying renewable energy products and systems. India is the only country in the world to have an exclusive ministry for renewable energy development, the Ministry of New and Renewable Energy (MNRE). Since its formation, the Ministry has launched one of the world's largest and most ambitious programs on renewable energy. In India 160 GW are currently powered by renewable energy sources (40% of total installed capacity in the year 2022. India has committed for a goal of 500 GW renewable energy capacity by 2030. In Maharashtra solar has a potential of over 75GW for solar power generation. The average solar radiation of Parbhani district is 5.30 kWh/m^2/d.

Most irrigation pump sets commonly rely on either electricity or diesel for operation. However, due to limited access to electricity in certain areas, diesel pumps are frequently used. To address this challenge and provide a solution for irrigation, the development of solar water pumping systems has been undertaken. These systems are capable of powering various types of motors and pumps, whether they are AC or DC. The aim is to resolve the problems faced by farmers, such as the absence of electricity in the field for irrigating their land, through the design and implementation of solar-powered water lifting systems.

Methodology

Design of carrier for spv water lifting system

Different components were designed and selected according to requirement. Mobile solar operated spv carrier consist of following components.

1. High clearance carrier
2. Solar power unit
3. Solar photovoltaic panel (SPV)
4. Main frame
5. Power supply, cables, VFD, controller and switch board
6. Water lifting unit

The step wise process for design and selection of various components of mobile solar operated spv carrier is explain below

High clearance carrier

In a high clearance carrier Platform is design to accommodate all the components. It is used for holding all the components and mobility of complete unit at various locations and within cropped field.

Specifications of carrier in mm

1. Base length of carrier = 3950
2. Base width of carrier=1350
3. Wheel track width (Adjustable) = 1550
4. Ground clearance=300
5. Diameter of ground wheels= 600
6. Diameter of hub wheels= 130
7. Rim width of wheels= 160
8. Length of beam= 1260
9. Material of ground wheels= Rubber

Solar power unit

The solar power component of a Solar Photovoltaic (SPV) water pumping system comprises solar photovoltaic panels, batteries, a primary structure, main frame with tracking system, power supply cables, variable frequency drive and a control panel.

Fig 1: Solar power unit

Solar panel capacity

Solar panel is used to generate the electrical power which further can be used to run the A.C motor with help of VFD, also running different machine in agro-processing unit, and to lift water. A solar panel of 335 W capacity the 415 V voltage and 8.95 A current was selected. A solar panel required for operating 3 hp three phase motor was calculated as 2.348 kW, hence more than requirement of motor 2.348 kW output solar panels was selected.

Solar photovoltaic modules

Solar photovoltaic (SPV) modules serve as the core component of a solar power unit, responsible for converting solar energy into electricity. This electricity can then be utilized to power various electrical appliances on the farm or stored in batteries for future use as needed. To determine the appropriate solar PV modules for the system, two key factors are considered: the power requirement for operating the appliances/devices, and the maximum panel size that can be accommodated on the cart without compromising its mobility on rural and farm roads. By taking these considerations into account, the most suitable SPV modules in terms of capacity and size was selected for the specific application.

The primary consideration in designing the solar mobile energy carrier was the available space for installing solar panels on the top of the carrier. By considering the dimensions of the carrier and its mobility on rural and farm roads, the designated area for panel installation was limited to 14.4 m^2 (6 m × 2.4 m).

To identify the most efficient panels that could be accommodated within this limited space and generate maximum electricity, a market survey was conducted. As a result of the survey, solar panels with a rating of 3 kW were chosen as they perfectly fit within the available space and provide optimal electricity generation capabilities. Also, on an average 3kW electric motor is generally preferred for irrigation by the farmers.

The primary objective behind developing the solar mobile energy carrier was to offer a portable solar power solution to farmers in remote areas where access to electricity is limited or non-existent. During the design phase, the carrier was envisioned to serve two crucial functions on farm and off farm: firstly, to facilitate water lifting for irrigation purposes, and secondly, to meet the various energy needs of the farmer like to operate agro processing unit and battery charging station. Solar photovoltaic modules were also intended to be utilized as a mobile solar power source for agro processing units and as a battery charging station. This multipurpose functionality aimed to enhance the productivity and convenience for farmers, allowing them to power agro-processing machinery and charge batteries for other applications, all through a mobile and renewable energy solution.

Modules are connected in series with 3 phase and 1 phase VFD to generates the required voltage and current suitable to supply power to controller.

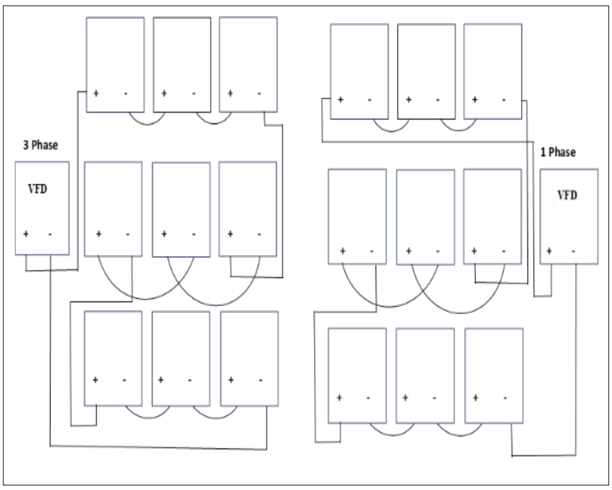

Fig 2: Modules connected in series having 3 Phase, & 1 Phase VFD

Table 1: Specifications of single solar PV panel

Sl. No.	Description	Specifications
1	Solar module Operator	Jyoti tech Solar
2	Model	JTS 335
3	Cell type	Multi crystalline silicon
4	Maximum power (p max)	335 W
5	Rated current	8.72 A
6	Rated voltage	38.45 v
7	Short circuit current	9.32
8	Open circuit voltage	46.04 v
9	Tolerance on the peak power	+ 5%
10	Size	1996×990 mm
11	Module area	1976040 mm^2
12	STC	Irradiance 1000 W/m^2 and cell temperature 25 ^0C

Power supply cables and switch board

Standard cables and switch boards were used to carry dc current from panel batteries and other appliances.

Variable Frequency Drives (VFD)

Controllers are Variable Frequency Drives based which works on both solar and electricity, available in three phase low voltage and high voltage AC Motors our controllers are designed with low maintenance cost. Its soft starter feature prevents hammering and increases life of the motor. Principle of VFD Pulse Width Modulated Variable Frequency Drives. When operated from a constant frequency power source (typically 50 Hz), AC induction motors are fixed speed devices. A variable frequency drive controls the speed of an AC motor by varying the frequency supplied to the motor.

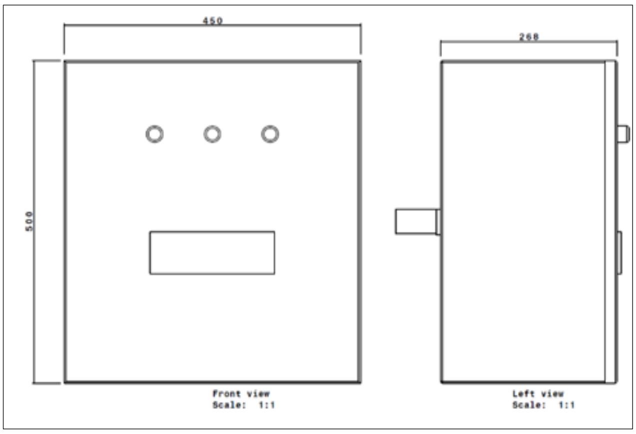

Fig 3: Variable Frequency Drive

Design of attachments for energy cart

Water lifting

AC pump

The use of an AC (Alternating Current) pump in water lifting offers several advantages, especially in the context of a solar mobile energy carrier designed for remote farming areas. AC pumps are known for their higher energy efficiency compared to traditional AC (Alternating Current) pumps. An AC motor is class of electrical machines that converts the alternate current electrical power into mechanical power. This mechanical energy is transferred to machine pulley which produces the required torque needed for operating different machine to make them a perfect match for the solar power generated on the mobile energy carrier. flexibility is essential for optimizing water usage and adapting to different crop requirements

The pump out put in liter/minute was determined in accordance with Kaul and Suleiman (1990) [3] with following formula,

Pump output (lit/min) = $\frac{S \times AR \times V}{600}$ (1)

Where,
S= Swath width
AR= Application rate(L/ha)
V= speed (km/h)

The pump was selected according to the hydraulic head or pressure requirement because it governs the hydraulic power required to produce a particular discharge.
Hydraulic power of pump will be calculated by the formula (Swami *et al.*, 2016) [7].

Hydraulic power (W) = p g h Q (2)

Where,
p = Water density (1000 kg/m^3)
g= acceleration due to gravity (9.81 m/s^2)
h=hydraulic head (m)
Q= Flow rate (m^3/s)

Pump capacity= $\frac{Hydraulic\ power}{efficiency\ of\ pump}$ (3)

Pump size

Hydraulic power of pump was calculated by the formula

Hydraulic power (W) = p g h Q

Efficiency of pump was taken as 60% (Narrate and Waghmare, 2016) [4].

Discharge

The volume of water delivered by pump per unit time m^3/h or m^3/sec. The discharge of the AC pump used in the test was measured by volumetric method by collecting the water in 200 liters tank and the subsequent time taken to fill the container was recorded using stopwatch. The same was repeated for five trails and the average of five trails was considered. (Priyanka *et al.*, 2018) [6].

Discharge was calculated using following formula,

$Q = \frac{Volume}{Time}$ (4)

Where,

Q = Discharge of water, m^3/s or l/s
V = Volume of tank, m^3 or l/s
T = Time to fill the tank, s

Total dynamic head of the pump

The total dynamic head (TDH) is composed of the three components i.e., total static head, friction head losses, and minor head losses. The total static head is the difference in height between the water source and crop. The average total head of farm pond was kept constant at 10 m for determination of pump discharge. The SPV pump is suitable to operate the drip irrigation system at 10 m. Total dynamic head was determined using following formula.

$$TDH = hs + hf + hm \quad (5)$$

Where,
hs = Static head
hf = Friction head loss
hm = Minor head loss

Pump horse power, hp

Total pump horse power required to lift the water from the particular head and discharge is calculated with the following formula,

$$HP = \frac{Q \times TDH}{75 \times \eta} \quad (6)$$

Where,
HP = Horse power, hp
Q = Discharge, lit/ sec
TDH = Total dynamic head, m

Table 2: The Specifications of selected AC pump set are shown in Table

AC Motors	Type	Induction Motor
	HP	2.0/3.0
	Rated current	3.8 A
	Speed	1440 rpm
	Voltage	415
	Frequency	50 Hz
	Efficiency	81%

Water lifting

The developed solar power plant was used to operate existing AC as well DC pump up to 3 kW capacity. The power unit could be brought to the installed pump it could be operated by using solar power source consists of solar panel, AC/DC VFD and controller.

Experiment procedure

The performance of SPV generating system for operating existing pump were conducted and the data was recorded hourly and from 10 am to 5 pm at the farmer's field. The performance parameters such as, solar radiation, atmospheric temperature, panel temperature, current, and voltage were recorded. The discharge rate was also studied throughout the experiment.

Operating speed of bullocks

Bullock pair was used to hitch the energy cart in the field during water pumping operation. The speed of the bullock's during operation was measured by marking 60 m distance on the field and recording time required to cover the same distance with the help of stopwatch. The data was recorded by conducting the trial for three times and average speed of travel was calculated.

Power requirement

Power required to operate mobile solar energy cart includes power required for pulling the cart by bullocks and solar power required to run the sprayer. The power requirement increases as the size of machine increases. It also depends upon field conditions and speed of operation.
The power required for pulling the solar energy cart in the field during spraying operation was calculated by the following formula.

$$HP = \frac{draft(kg) \times speed\ m/sec}{75} \quad (7)$$

Where,
Draft = Horizontal component of pull = P cos θ
P = Pull, Kg
θ = Angle made by line of pull with horizontal in deg.
Pull force

Discharge measurement of pump

The pump was tested to ensure its proper working and discharge at different pressures or heads. The pressure gauge and control valve were fitter on delivery pipe. The required pressure was set by adjusting control valve and discharge was measured. The discharge of the pump was calculated by measuring time required for filling the container of known volume with water. The readings were taken at different pressures and repeated three times to get an average value.

Performance evaluation solar photovoltaic panel

Panel testing

IV characteristics

The current I (A) and voltage (V) generated by the PV array was recorded every hour of the sunny day from 10 am to 5 pm using AC ammeter. To measure the output current and voltage of the PV array the multi meter was connected directly to the power supply terminals of the PV array.

Solar intensity

Solar intensity denotes the quantity of solar energy present in a particular area, directly impacting the output of solar panels. To gauge solar intensity, a Pyranometer, a specialized device, was utilized. This tool captured solar intensity data at consistent one-hour intervals, spanning from 10:00 AM to 5:00 PM.

Voltage generated

The researchers or technicians employed a multi-meter to gauge and log the mean voltage generated by the solar panel while it was actively engaged within the agro processing facility. Through the utilization of the multi-meter, the individuals in charge could oversee and appraise the steady voltage production of the solar panel during its operation. The multi-meter was utilized to measure the mean voltage generated by the solar panel while it was operating alongside different machines.

Frequency of Current

The frequency of an electric current signifies the number of complete cycles of the waveform that occur in a single second and is quantified in hertz (Hz). Household electrical power, characterized by a sinusoidal wave shape, maintains a frequency of 50 Hz.

Current

The multi-meter was employed to measure the mean current generated by the solar panel while it was in operation with various machines.

Atmospheric Temperature

Solar cells exhibit sensitivity to alterations in temperature. Elevated temperatures lead to a reduction in the band gap of the semiconductor material, consequently influencing various characteristics of the material. This decline in the semiconductor's band gap due to rising temperatures corresponds to an augmentation in the energy possessed by electrons within the material.

Power produced

The power generated is determined by multiplying the voltage and current produced by the solar panel while it is in operation.

Field performance of AC pump for water lifting

The performance of AC pump run by mobile energy cart for water lifting was evaluated by using incident solar radiation, effective module area, output voltage, output current, total head and discharge. The overall efficiency of the solar pumping system was calculated as follows

Efficiency of PV system

Electrical power conversion efficiency of the PV system is the ratio of the amount of electricity generated by PV system to the amount of solar energy incident on the surface of the PV array and it was calculated by following formula (Ozturk *et al*., 2016) [5].

$$\eta_{PV} = \frac{Isc \times Voc}{St \times A} \quad (8)$$

Where,

η_{PV} =Efficiency of PV system, %

I_{SC} = Short circuit current, A

Voc= Open circuit voltage, V

S_t= Total solar radiation, W/m²

A = Surface area of the PV module/array, m

Efficiency of the pump

$$\eta_P = \frac{Ph}{Pf} \quad (9)$$

Where,

η_P = Efficiency of pump, %

P_h= Hydraulic power of the pump, kw

P_f = Input power to the pump, Kw

Overall efficiency of the solar pumping system

$$\eta s = \eta_{PV} \times \eta_P \quad (10)$$

Where

ηs = Overall efficiency of solar pumping system, %

η_{PV} = Efficiency of the PV module/array, %

η_P = Efficiency of pump, %

Results

Performance evaluation of bullock drawn mobile solar power source for water lifting

Bullock drawn mobile solar power generating system was field tested for water lifting, agro processing unit and as a battery charging station at farmer's field. The hourly observations of solar insolation, ambient and panel temperature, array output volage & current, pump input voltage & current, pump discharge, was taken in October. The analysis of field test data was carried out to calculate pump discharge and pumping system efficiencies during October month presented in table 3

The variation of solar insolation and pumping system efficiency (array efficiency, pump efficiency) with respect to time is graphically shown in fig 4.

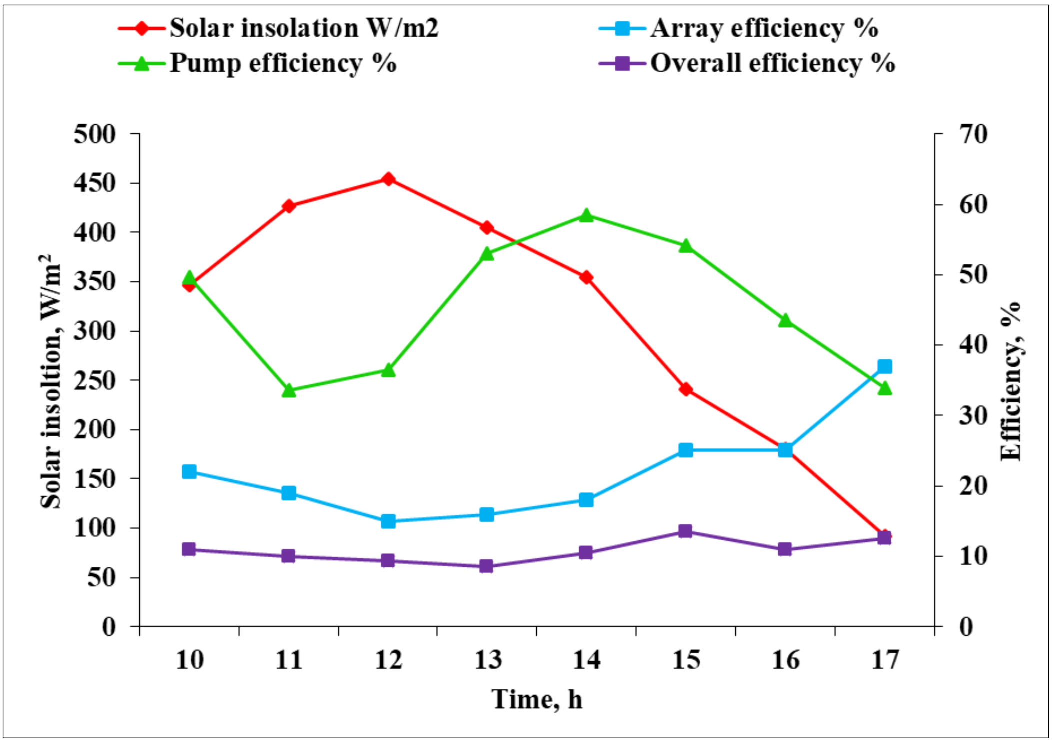

Fig 4: The variation of solar insolation and pumping system efficiency with time

Table 3: performance of pump

Time, h	Head m	Solar Insolation W/m2	Ambient Temp, ^{0}C	Panel temp ^{0}C	PV array Voltage, V	Currently A	Power w	Array efficiency % p,	Pump input Voltage, V	Current, A	Power w	Time taken to fill 200-liter tank(min)	Pump discharge lpm	Pump discharge m^3/s	Hydraulic power W	Pump Efficiency, %	Overall efficiency%
10 am	25	347	28	49.9	331	3.3	1092	22	329	2	658	2.5	80	0.0013	326.6	49.63	10.91
11 am	25	427	29	52	310	3.7	1147	19	307	3.6	1105	2.2	90.9	0.0015	371.1	33.58	6.38
12 pm	25	455	30	54	304	3.2	972.8	15	301	3.1	933	2.4	83.3	0.0014	340	36.44	5.47
1 pm	25	405	30	57	307	3.0	921	16	302	1.7	513.4	3	66.6	0.0011	272.3	53.03	8.48
2 pm	25	355	31	49	315	2.9	913.5	18	310	1.4	434	3.2	62.1	0.0010	253.5	58.41	10.5
3 pm	25	241	32	41	338	2.5	845	25	335	0.9	301.2	5	40	0.00007	163.3	54.21	13.55
4 pm	25	180	29	39	320	2.0	640	25	312	1	312	6	33.3	0.00006	135.9	43.55	10.9
5pm	25	92	28	38	321	1.5	481.5	37	318	1.2	381.6	6.3	31.74	0.00005	129.6	33.96	12.6
Avg	25	312.8	29.5	47.4	318.3	2.7	859	19	314.3	1.8	565.7	3.8	60.9	0.0001	248.6	43.94	8.34

Table 4: Speed of bullocks, draft and power required to pull mobile solar operated power generating system

Replications	Distance Travelled m	Time, sec	Speed, km/h	Speed, m/s	Draft, kg	Power, hp
R1	600	264	8.17	2.27	37.2	1.12
R2	600	260	7.99	2.22	35	1.03
R3	600	262	8.24	2.29	40	1.22
Avg	600	262	8.13	2.26	37.4	1.12

Table 5: Speed of bullocks, draft required to pull mobile solar energy cart for water pumping off road

Replications	Distance Travelled m	Time, sec	Speed, km/h	Speed, m/s	Draft, kg	Power, hp
R1	160	147	3.88	1.08	54	0.77
R2	160	145	3.96	1.10	52	0.76
R3	160	148	3.88	1.08	51	0.73
Avg	160	146.7	3.9	1.08	52.3	0.75

From Table 3 it is observed that during winter season maximum pump discharge of 90.9 lpm was found at 11:00 h and maximum pump efficiency of 58.41 per cent was found at 2 pm of the day with corresponding solar intensity of 455 W/m^2. The pump was operated in the ambient temperature range of 28 to 32 ^{0}C, panel temperature range of 38 to 57 ^{0}C with solar insolation ranging between 92 to 455 W/m$^{2.}$. the average array efficiency, pump efficiency and overall efficiency of solar pumping system was 19%, 43.94% and 8.34% respectively. The pump delivered almost constant discharge between 62.1 to 90.9 lpm between 10:00 am to 2: 00 pm.

Field performance of mobile solar power generating system

The field performance of mobile solar power generating system was carried out on and off road. The developed mobile solar power generating system was field tested. A pair of deoni breed of bullocks was used for hauling energy cart on and off road. The pull force was recorded using dynamometer mounted between yoke and beam.

Speed of bullocks, draft and power required to pull mobile solar energy cart

The speed of bullocks, draft and power required for pulling mobile solar power generating system was determined and results are presented in Table 4 and 5
below.

From the table 4, the draft worked out to 35 to 40 kg with an average draft of 37.4 kg. The average speed of bullocks during the operation was observed as 2.26 m/s (8.13 km/h). the average power required for pulling mobile solar power generating system is 1.12 hp.

From the table 5, the draft worked out to 51 to 54 kg with an average draft of 52.3 kg. The average speed of bullocks during the operation was observed as 1.08 m/s (3.9 km/h). the average power required for pulling mobile solar power generating system off the road is 0.75 hp.

Conclusion

1. Existing AC pump was operated by solar power generating system delivered discharge in the range of 90.9 to 33.3 lpm for the solar insolation ranging between 455 to 92 W/m^2.
2. The solar pumping system attained the highest overall efficiency of 13.55% during winter.
3. The pump efficiency was maximum, when the insolation was maximum and this occurs at 12.00 h of the day. The overall efficiency of the pumping system remains fairly constant for all the seasons. There was general trend of increasing overall efficiency of solar pumping system when days were started becoming warmer.

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