Investigational Analysis and Experimental Study of a 3-phase Induction Motor for Electric Bike Application

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Abstract:- With the advent of global warming and rapid incentivization of electric vehicles being manufactured, research on new and efficient models of the same becomes highly imperative to offer innovative solutions to fundamental issues that limit the market penetration. The current Indian Electric Two-wheeler (E2W) segment utilizes limited motor technologies pertaining to the need of permanent magnets. This work aims to reduce this need by investigating the use of the Asynchronous AC motor as an alternative to magnet motors and experiment with their respective drive system for feasibility of operation. The study proves the hypothesis of a more efficient and cost friendly alternative for an E2W powertrain.

Keywords:- *Electric Two-Wheeler, Battery Powered Bike, Asynchronous Motor, Electric Powertrain, 3-phase AC Drive.*

I. INTRODUCTION

The beginnings of the 21st Century is notably remarked for its emergent actions and discussions over the climate issues that we face. A major contribution to today's global pollution levels comes from the conventional ICE driven automobiles; over one-fourth of the global emissions come from the tailpipes. Electric Vehicles are arguably the most efficient and clear alternative but the technologies in itself face a lot of challenges to successfully penetrate the market and thus limits the consumer adaptation. The Indian EV market is currently dominated by E2Ws due to their ease of riding and evident advantages over their combustion engine counterparts. However, even the E2W segment in India is limited to its graphic innovations whereas the key powertrain elements remain the same. This research work aims to investigate the use of an Asynchronous 3-phase AC motor to drive a motorcycle and experiment with a Variable Frequency Drive to control the speed of the vehicle. It utilizes a Lithium-Ion Battery as its power source for its well-known advantages of higher energy density and power density. The low DC voltage of the battery pack is converted to High AC voltage to operate the motor used. The paper further aims to analyze the powertrain respectively to assess areas of improvement and provide a more tangible and cost friendly solution.

II. LITERATURE REVIEW

For our project, we intensively studied some fundamental concepts on the technologies and topologies pertaining to the various elements of the powertrain. The research papers were read thoroughly to understand the respective knowledge and a summary of key findings is shown here.

Chili Jin [1] makes it easy for one to comprehend various electric motor technologies for electric vehicle applications. Apart from their structure, principle and performance, Jin proposes a small list of advantages and disadvantages for each of the motor types based on EV application.

Hicham El Hadraoui, et al. [2] provides the technological aspect of the different components of the electric powertrain and highlights the important information on the electric vehicle's architecture. The main highlight of this paper is a multi-criteria comparison of different electric motors utilized in the electric traction system. The presented analysis compares and shows that the asynchronous motor meets the major requirements of the electric powertrain, whereas the permanent magnet motors are nonetheless still majorly chosen by electric vehicle manufacturers.

The project by **Suraj Kudale, et al. [3]** presents the Structural and Dynamic Investigation of Electric Motorcycle Chassis and the design of a new model motorcycle chassis and to find the modal properties of the structure and comparatively analyse them through experimental modal analysis and FEA.

Ergashali Rakhimov, et al. [4] was quite helpful in understanding and comparing various battery technologies for Energy storage. We took the liberty to extrapolate the findings for effective EV applications.

Donghwan Ji, et al. [5] presents Trend of Developing Aqueous Liquid and Gel Electrolytes for Sustainable, Safe, and High-Performance Li-Ion Batteries. This paper reviews possible ways for the implementation of aqueous Lithium-ion batteries with enhanced electrolyte–electrode interfaces.

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K. M. Sahana, et al. [6] presents a research on BLDC motor used in an E-bike and performs a parametric study to predict torque range improvements and a further parametric analysis on the variations in shape of slots, poles per phase, dimensions of slots, stator and rotor materials.

A PhD synopsis by **Mayank Pratap Singh [7]** titled "Parameter Estimation of Three Phase Induction Motor: An Innovative Approach" gave a comprehensive introduction to the understanding of the parameters surrounding induction motors and troubleshooting various faults in both designing, operating and developing an induction motor.

The world-renowned paper by **V.B. Honsinger [8]** on Sizing equations for Electrical Machinery published in 1987 proves to be the fundamental approach towards designing and optimising the dimensions of an induction motor stator core. This helped us in the analysis of our current motor design and the further power optimization using the equations.

Pedro H. Camargos, et al. [9] presents a highly comprehensive study comparing the use of induction motors in light EV applications. Through simulating in the ADVISOR software, the torque characteristics of the considered induction motor was compared with the other magnet motors, similarly made for light electric vehicle applications.

The paper by **S. O. Kwon, et al. [10]** deals with the loss distribution of a three-phase induction motor considering operating point-of-core material based on the FEA and experiments. The results guide us in selecting core materials to improve motor efficiency.

Cenk Ulu [11] provides an analytical approach towards the Electromagnetic and Thermal Design and Analysis of an Induction Motor for Electric Vehicles. The results obtained in the electromagnetic analyses directs the modification in the induction motor to enhance the performance.

Payam Shams Ghahfarokhi, et al. [12] underlines and aims to solve the high AC losses at high speeds due to the Hairpin Windings. The paper proposes two methods: correct transposition of conductors in parallel paths and enhancing the number of conductor layers in a slot.

Sameer Madhavan, et al. [13] provides a comprehensive review of the thermal management strategies applied in the industries for induction motors by studying methods including finite element analysis, lumped parameter thermal network and computational fluid dynamics tools.

Igors Uˇsakovs, et al. [14] discusses in this paper the technology based on modular standardized approach for Loop Heat Pipe (LHP) design and manufacturing. To experiment, authors used a double-capillary pump unit and an evaporator LHP was made and installed inside a hub motor. Electric Motor thermal characteristics were studied and compared to the values obtained prior to LHP installation.

Mehmet Onur GULBAHCE, et al. [15] presents a comprehensive numerical optimization approach on optimizing the slit dimensions of an Axially-Slitted Solid Rotor Induction Motor (AS-SRIM) while benefits of plunge type electrical discharge method was used to open narrower slots.

Chengling Lu, et al. [16] aims to achieve the optimal performance of a special pole bearingless induction motor through a multi-objective optimization design based on a bi-level optimization scheme.

Hadi Aghazadeh, et al. [17] gives an insight into tackling key issues in designing a Synchronous Reluctance Motor. The study presents a comprehensive design procedure of an external rotor synchronous reluctance machine suitable for an electric bike application. The initial rotor design is made to test the multi-objective optimisation in order to provide further enhancement to the torque performance.

X. D. Xue, et al. [18] proposes a multi-objective optimization for designing switched reluctance motors. The optimization function that is devised is chosen as the correct trade-off between the maximum values of the average torque, the average torque per copper loss, and the average torque per motor lamination volume, by using three weight factors and base values.

Hassan Moradi CheshmehBeigi, et al. [19] presents an analytical approach along with an electromagnetic field analysis, and parametric analysis of an external rotor permanent magnet-assisted SRM. The rotor geometry is analysed and modified to obtain the least torque ripple and most electromagnetic torque with utilizing numerical analysis based on 2D FEA method.

Ali Mansouri, et al. [20] presents an excellent paper on multi-objective optimization of an in-wheel surface mounted permanent magnet motor (SMPM) with outer rotor and concentrated windings. The aim of this optimization analysis is to attain the optimum design geometry by maximizing the motor's efficiency and reducing its weight. Two objective functions are used for this; A design with high output torque capability and then high efficiency and a requirement of light weight.

K. Vijaya Bhaskar Reddy [21] has extensively studied and investigated certain VSI fed induction motor drives. The main objective was to develop a cost effective, simple and efficient high-performance drive. A space vector modulation is more advantageous due to low harmonic production.

Mirza Abdul Waris Begh, et al. [22] comprehensively compares two of the most popular vector control methods for electric motor drives; Field Oriented Control and Direct Torque Control. The comparative analysis is based on various criterion that includes rudimentary control characteristics, transient performance, parameter sensitivity, and complexity of implementation.

Brahim Gasbaoui, et al. [23] proposes a control method that ensures both safety and stability of the electric vehicle by the means of Direct Torque Control which ensures efficiently controlled vehicle.

In the paper by **Jun-Koo Kang, et al. [24]** a direct torque control (DTC) method of an induction machine is proposed which improves the performance of the DTC by combining a low-torque-ripple characteristic in steady state with the fast torque dynamics at constant switching states.

Kai Zhao, et al. [25] proposes an on-board controller that adopts the form of a time-sharing multiplexing IGBT power module to simultaneously realise motor drive and battery charging whose working principle is explained in the paper. The mathematical model of the converter in driving and charging modes is analysed, and the control strategy in the two modes is determined.

Dae Kyung Kang, et al. [26] proposes a test method to measure the road load of e-bikes driven by in-wheel brushless DC (BLDC) motors during a road drive where speed and road load were correlated by fitting the speed and current consumption of the motor when driving at constant speed on a uniform horizontal road to realise a linear relation.

Sanjana Malhotra [27] presents the techno-economic design and its implementation of protection circuits for IGBT based Voltage Source PWM Inverters and Health Monitoring of Variable Speed AC drives for applications like rolling mills, paper mills, traction mobility, etc.

III. RESEARCH METHODOLOGY

We propose this research study that encompasses both the aspects of an investigational analysis and experimental study of the powertrain elements. An outline of the stages involved for this is as follows:

- Market research on the current trends in technologies that are provided by brands followed by an analysis to comprehend the available options and scope a gap.
- Investigate and Analyse research papers to understand and choose from various technologies pertaining to electric two-wheeler powertrain such as electric motors, control strategies, battery systems, etc.
- Choosing design strategies to be followed that falls under both electrical and mechanical setup of the powertrain for experimental study.
- Prototyping for experimenting and measuring the results from the created setup to conduct analysis.
- Dynamic Analysis of the powertrain to assess performance and efficiency with regard to consumer demands.

IV. INVESTIGATIONAL ANALYSIS

Inductions motors account for more than 70% of the industrial application due to its robustness and high efficiency with low cost. Induction motors are characterised for their simple design and optimal performance but they are limited with inefficiencies such as slip and low torque. Yet there is an increasing amount of research done to optimise the performance, especially with respect to its EV applications.

Such was a review which shows Induction motors to be more advantageous for EV application in contrast to popular belief [2]. Various motor technologies are compared on the aspects of performance, reliability and efficiency. An analysis is done for these aspects and the result for BLDC and Induction Motor is shown below in Table 1:

Table 1 Investigational Analysis

	Induction Motor	**BLDC Motor**
Performance:		
Power Density	Medium	Very High
Dynamic Response	Medium	High
Torque Ripple	Very Low	Low
Max Speed	High	Medium
Max Torque	Medium	Very High
Speed Range	Medium	Medium
Noise Level	Medium	Very High
Acceleration	High	High
Reliability:		
Robustness	High	High
Overload Capacity	High	High
Fault Tolerance Capacity	High	Low
Maintenance	Not required	Not required
Life	Very High	High
Maturity	Very High	High
Commutation	Not required	Required

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Slip	Present	Not present
Efficiency:		
Controllability	High	Low
Cost	Very Low	High
Size	Medium	Medium
Max Current	Very Low	Very High
Power Source	High Capacity	Medium Capacity
Weight	High	Very High
Thermal Management	Difficult	Highly Difficult

A characteristic comparison shown in Fig 1. using specified formula gives a clear understanding of the different motor types.

This analysis clearly presents a higher efficiency and reliability characteristics. However, it poses a challenge of implementing a lower performance in contrast to BLDC motors. Although BLDC motors have been a popular choice amongst E2W manufacturers in India along with PMSM motors, we aim to harness the advantages and simplicity of using an Induction motor in an E2W powertrain.

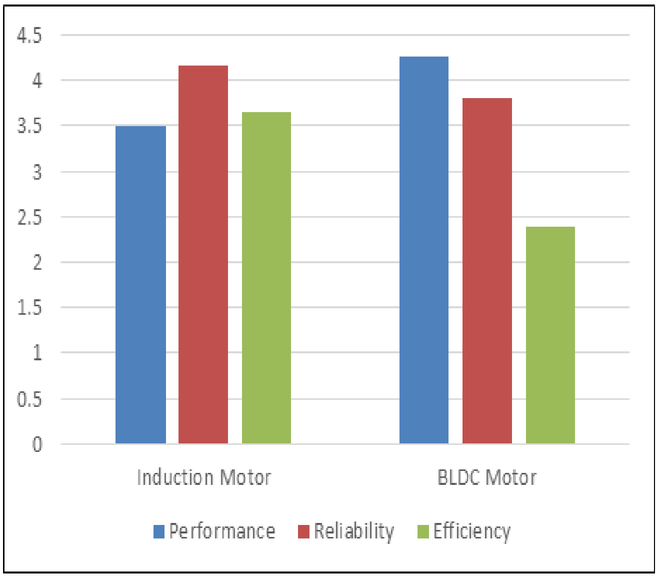

Fig 1 Characteristic Comparison between Motor Types

A. *Experimental Setup*

Here, we have divided the powertrain into 4 main elements and their detailed specification is given below:

- *Power Source –*

As the power supply we used a Li-ion Battery Pack of 960 Watt-hour; four 12-volt 20Ah batteries connected in parallel. The individual batteries are of NMC type and were of dimensions 7x6x20 cm amounting to a power density of the entire battery pack to be around 285 KWh/m^3.

- *DC to AC converter –*

The conversion from 12 Volt DC to 230 Volt AC (single phase) is carried out by a 900VA/756W inverter. The inverter comes with a variety of options such as low battery indication, overcurrent protection and in-built battery charging capability.

- *3-phase Modulation –*

To operate the motor, we utilized a Variable Frequency Drive which converts the single-phase AC into 3-Phase AC whose frequency can be modulated using a potentiometer. The VFD utilizes a V/F conversion to convert the single-phase AC into DC and then switching the DC into a quasi-sine wave AC of 3 phases. The VFD also has a feature of increasing the torque of the induction motor by allowing a higher current at lower voltage levels. The VFD secures the motor from overcurrent, undervoltage and high temperature risks.

Fig 2 3-phase Induction Motor

- *Electric Motor –*

For the prime mover we are using an Asynchronous (induction/squirrel cage) 3-phase AC motor with 1hp/0.75KW of rated power at 415 Volts (star connected) and 1.9 Amps. The torque varies at different frequencies and can be controlled with current and voltage levels.

- *Auxiliary –*

The battery, Inverter and VFD are secured in an arrangement as shown and wired in series as shown. The motor is connected to a multi-speed gearbox whose ratios are listed in the table as shown. The final drive is a chain that drives the rear wheels.

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Fig 3 Motorcycle Chassis

The chassis we are using is OEM and for strictly experimental purpose; not modelled for EV application by us. The brakes, suspension, steering and wheels are unaltered for safety and convenience. The model is a prototype and serves as a Proof of Concept to test the hypothesis of our powertrain under real world driving conditions.

B. Experimental Assembly

The parts are assembled by first disassembling the motorcycle to get rid of all its ICE components such as the fuel filter, carburettor, engine, gearbox, chain, battery (lead-acid) and other auxiliary parts. Moreover, the wiring is also avoided by leaving the important safety elements such as brake light and speed sensors. The chassis is analysed for the allocations allowed which can be suited for our project well and thus the placement of the powertrain parts is executed:

➢ *Battery –*

The battery is of a relatively compact design and thus allows for a sturdy pack that can be placed in the space as shown in a T-shaped arrangement. This allows for an enclosed packing with minimal exposure to the surroundings to avoid higher heating temperatures.

➢ *VFD –*

The VFD used was of minimal dimensions and required reachability for control and connectivity from the battery, control switches and the motor. We ingeniously placed the module by making a opening in the fuel tank which allowed a direct view of the module screen and the wires were fed through a slit made at the bottom of the tank.

Fig 4 Battery Pack with a Preliminary Switch


Fig 5 VFD Placed in Fuel Tank

➢ *Motor –*

The induction motor was initially made to fit at the place where originally the gearbox was. However, after realising a lack of sufficient torque available at the wheels, we decided to fit the gearbox back in its place and providing the power to the crankshaft through a chain drive thus using a gear ratio of approximately 36:1 to provide necessary torque.

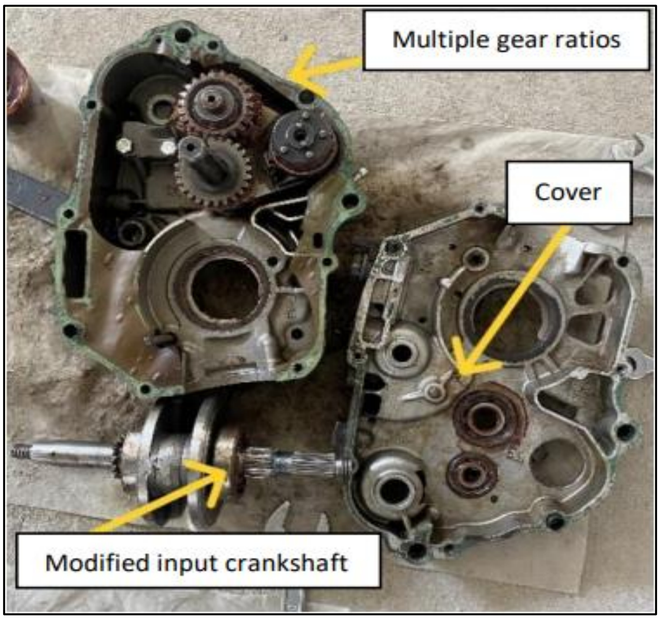

Fig 6 Disassembled Gearbox and Crankshaft

- *Gearbox Ratio:*

Primary reduction – 3.722:1
Final drive – 3.071:1

- *Total Ratio from Motor Shaft to Wheels in –*

1st Gear – 3.182:1; 3.722*3.182*3.071 = **36.371:1**
2nd Gear – 1.706:1; 3.722*1.706*3.071 = **19.5:1**
3rd Gear – 1.238:1; 3.722*1.238*3.071 = **14.15:1**
4th Gear – 0.958:1; 3.722*0.958*3.071 = **10.95:1**

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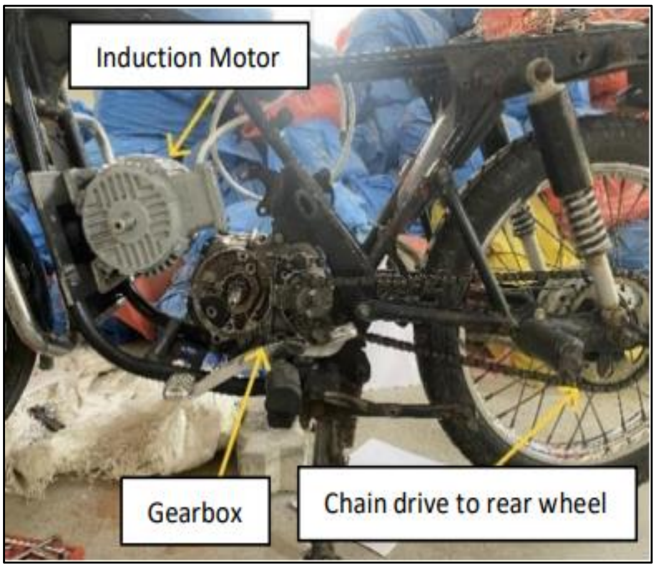

Fig 7 Motor Fitted on Chassis

➢ *Inverter –*

The Inverter was by far the most space consuming element due to its box-like design and weight. We initially planned it to be placed where the engine was, but due to the new motor placement, we had to create a new contraption near the rear right suspension to hold the inverter much like a luggage carrier. The wires were carefully drawn to avoid any electrical shock to the body or passenger. They were let under the seat to reach both the battery and the fuel tank to access the VFD. The casing was made with ventilation and the in-built fan of the inverter was not covered.

The electrical connections can be easily understood from the battery terminals to the motor terminals. The battery pack is created by connecting four 12-volt batteries in parallel to provide sufficient capacity. The 12-volt battery pack is connected to the inverter battery terminals via a preliminary switch. The inverter further converts this DC and supplies 230-volt single phase AC through its output socket. This is then connected to the VFD terminals as an input which then is used to modulate this single-phase AC into a variable frequency 3-phase AC which is supplied to the induction motor terminal box. The VFD, although, contains a potentiometer in-built next to its digital display, but it allows external control to alter the frequency. We utilized this feature to fit a potentiometer near the accelerometer of the motorcycle and connected to the analog terminals of the VFD, which allows the user to vary the 3-phase AC frequency supplied to the electric motor, consequently the speed of the motorcycle. In addition to the electrical speed control, the vehicle's speed can also be controlled through changing the gear ratios provided in the multi-speed gearbox.

The prototype is operated by first switching the preliminary switch that closes the circuit from the battery and inverter. The inverter is then turned on by a switch provided on its periphery. Further, the VFD calculates the input voltage and deems it to be sufficient to power the motor.

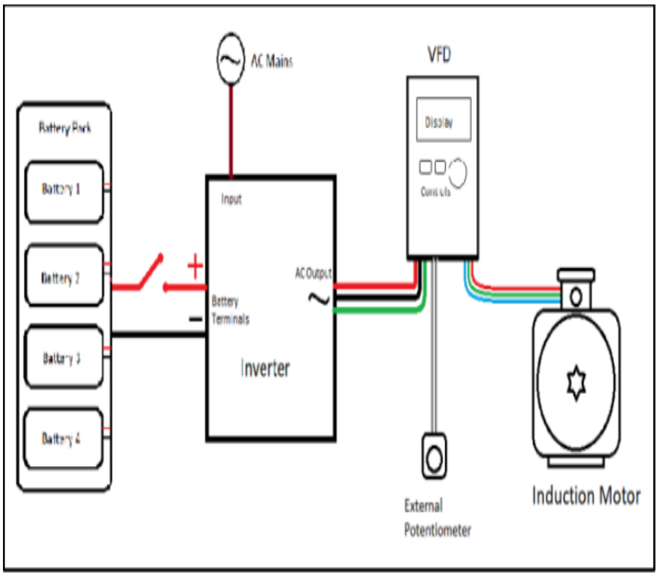

Fig 8 Line Diagram of Electrical Connections

The VFD requires the user to press a switch which then supplies the motor with 3-phase AC at 0.5 Hz. This can be increased up to 50 Hz using the potentiometer and then aligning the gearbox from neutral position to first gear, the power is transmitted to the rear wheels.

C. Dynamic Analysis

After testing the model during its operation, we were able to deduce the feasibility of the prototype to be fairly significant and the technology was unique due to a lack of experimental studies that challenge our proposed thesis. We were successfully able to operate the motorcycle with ease and convenience. The battery pack of 960 watt-hour was deemed to be of precise rating in respect to the motor used of a power rating of around 750 watts. The inverter and VFD were procured to sufficiently power the system without any safety or compatibility issues.

The operation of the model was successful; the motor, even though initially after failing to drive the wheels directly, could drive the motorcycle with the utilization of a multi-speed gearbox. This although reduced the speed in the initial gear ratios, but significantly improved the starting torque. The speed later could not only be increased with increasing the 3-phase AC frequency, but also by utilising the gear ratios available at the gearbox.

The battery was able to drive the vehicle under normal road conditions and zero slope for around 50 Kms from full charge to a complete discharge. The battery was not heated above ambient temperature that shows a safe working condition. The VFD showed a current usage of around 1.8 Amperes at around 170 Volts 3-phase AC at peak power requirement. The inverter and VFD were in operable condition due to the operation of their respective cooling fans and the motor was not heating above ambient temperature.

V. CONCLUSION

The project successfully summarises the key research areas that were hypothesized. The experimental study was carried out after intensively researching the market review and literature pertaining to E2W powertrains. The papers which were investigated suggested a direction towards utilising and harnessing the well-known advantages of the AC induction motor while tackling the challenges faced in its EV application. The primary challenge was to drive the motor which was satisfied by the use of a V/F variable frequency drive which can efficiently modulate the 3-phase AC frequency. Furthermore, the popular industrial use of induction motors fails to extract its high starting torque capabilities due to its desired applications. For experimental purposes we were able to use a gearbox that improves the torque capability of the motor. However, after a dynamic analysis and consequently optimising the key elements, one can devise an optimal design that supplies enough torque at low speeds that is sufficient for E2W application. Moreover, the control system was improvised using hysteresis comparators for a closed loop Direct Torque Control of the AC motor. This reduces the need of a gearbox, redundant user inputs and losses thus increasing overall efficiency of the vehicle. The study shows a clear alternative to the upcoming trends in E2W models and presents an innovative solution.

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