BLDC MOTOR FED BY SOLAR PV ARRAY FOR WATER PUMPING SYSTEM BASED ON LUO CONVERTER

Akhil Raj.B, Prakash.R

Department of Electrical and Electronics Engineering,NIET Coimbatore

Abstract —**This paper deals with the solar photovoltaic (SPV) array fed water- pumping system using a Luo converter as an intermediate DC-DC converter and a permanent magnet brushless DC (BLDC) motor to drive a centrifugal water pump. Among the different types of DC-DC converters, an elementary Luo converter is selected in order to extract the maximum power available from the SPV array and for safe starting of BLDC motor. The elementary Luo converter with reduced components and single semiconductor switch has inherent features of reducing the ripples in its output current and possessing a boundless region for maximum power point tracking (MPPT). The electronically commutated BLDC motor is used with a voltage source inverter (VSI) operated at fundamental frequency switching thus avoiding the high frequency switching losses resulting in a high efficiency of the system. The SPV array is designed such that the power at rated DC voltage is supplied to the BLDC motor-pump under standard test condition and maximum switch utilization of Luo converter is achieved which results in efficiency improvement of the converter. Performances at various operating conditions such as starting, dynamic and steady state behavior are analyzed and suitability of the proposed system is demonstrated using MATLAB/Simulink based simulation results.**

Keywords—SPV array; Luo converter; BLDC motor; Centrifugal water pump; MPPT; Switch utilization.

I. INTRODUCTION

Severe environmental protection regulations, shortage of fossil fuels and eternal energy from the sun have motivated the researchers towards the solar photovoltaic (SPV) array generated electrical power for various applications [1]. Water pumping is receiving wide attention nowadays amongst all the applications of SPV array. To enhance the efficiency of SPV array and hence the whole system regardless of the operating conditions, it becomes essential to operate SPV array at its maximum power point by means of a maximum power point tracking (MPPT) algorithm [2-4]. Various DC-DC converters have been already employed to accomplish this action of MPPT. Nevertheless, a Luo converter [5 -9] based MPPT is still unexplored in any kind of SPV array based applications. An incremental conductance (INC) MPPT algorithm [2] is used in this work in order to generate an optimum value of duty cycle for the IGBT (Insulated Gate Bipolar Transistor) switch of Luo converter such that the SPV array is constrained to operate at its MPP. Various configuration of Luo converters such as self-lift circuit, re-lift circuit, triple-lift circuit and quadruple-lift circuit using voltage-lift (VL) technique have been reported in Aforementioned topologies have high voltage transfer gain but at the cost of increased number of

components and switching devices. Therefore, these topologies of Luo converter do not suit the proposed water pumping system.

A negative output elementary Luo converter is used in this work to achieve the maximum power operation of SPV array. Proper control of Luo converter also facilitates the reduced current starting of BLDC motor. In , it has been reported that sensing of negative polarity signals calls for an additional circuitry, which badly affects the system responses/performances. Since the proposed SPV array fed water pumping system does not need converter output voltage sensing because it is not maintained constant, negative polarity output of Luo converter neither increases the proposed system complexity nor affects the system performance. Voltage transfer gain of an elementary Luo converter is identical to a conventional buck-boost converter but the Luo converter has smooth output current unlike a buck-boost converter. However, a small valued ripple filter may be required at the input to reduce the ripple contents of input current. The Luo converter has unrestricted region for MPPT operation because of its identical input-output relationship as the conventional buck-boost converter .Moreover, the Luo converter is designed to operate in continuous conduction mode (CCM) regardless of the various operating conditions offering the lower stress on the components and semiconductor switch of Luo converter. Maximum switch utilization [11] of Luo converter is also achieved with the same design method.

The permanent magnet brushless DC (BLDC) motor is employed to drive a centrifugal water pump coupled to its shaft. The BLDC motor is selected because of its merits [7,9] useful for the development of suitable water pumping system. This electronically commutated BLDC motor [9] is supplied by a voltage source inverter (VSI) which is operated by fundamental frequency switching resulting in low switching losses. Suitability of the proposed SPV array fed water pumping system subjected to various operating and environmental conditions is demonstrated by satisfactory simulated results using MATLAB/Simulink environment.

II. PROPOSED SYSTEM CONFIGURATION

The configuration of proposed SPV array fed water-pumping system employing Luo converter and BLDC motor drive is presented in Fig. 1. It consists of a SPV array feeding the water pumping system, a negative output elementary Luo converter as an intermediate DC -DC converter for MPPT, a three phase VSI supplying power to the motor-pump, a BLDC motor with inbuilt encoder to perform the electronic commutation by Hall signal sensing, a centrifugal water pump

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coupled to shaft of the BLDC motor and a pulse generator via the execution of INC-MPPT algorithm. When the MPP is reached, an optimum value of duty ratio is generated by INC-MPPT algorithm. This duty ratio is further converted, by comparison with high frequency saw-tooth carrier signal, into switching pulse for IGBT switch of Luo converter. Design, control and operation of each stage of the proposed system are elaborated in following sections.
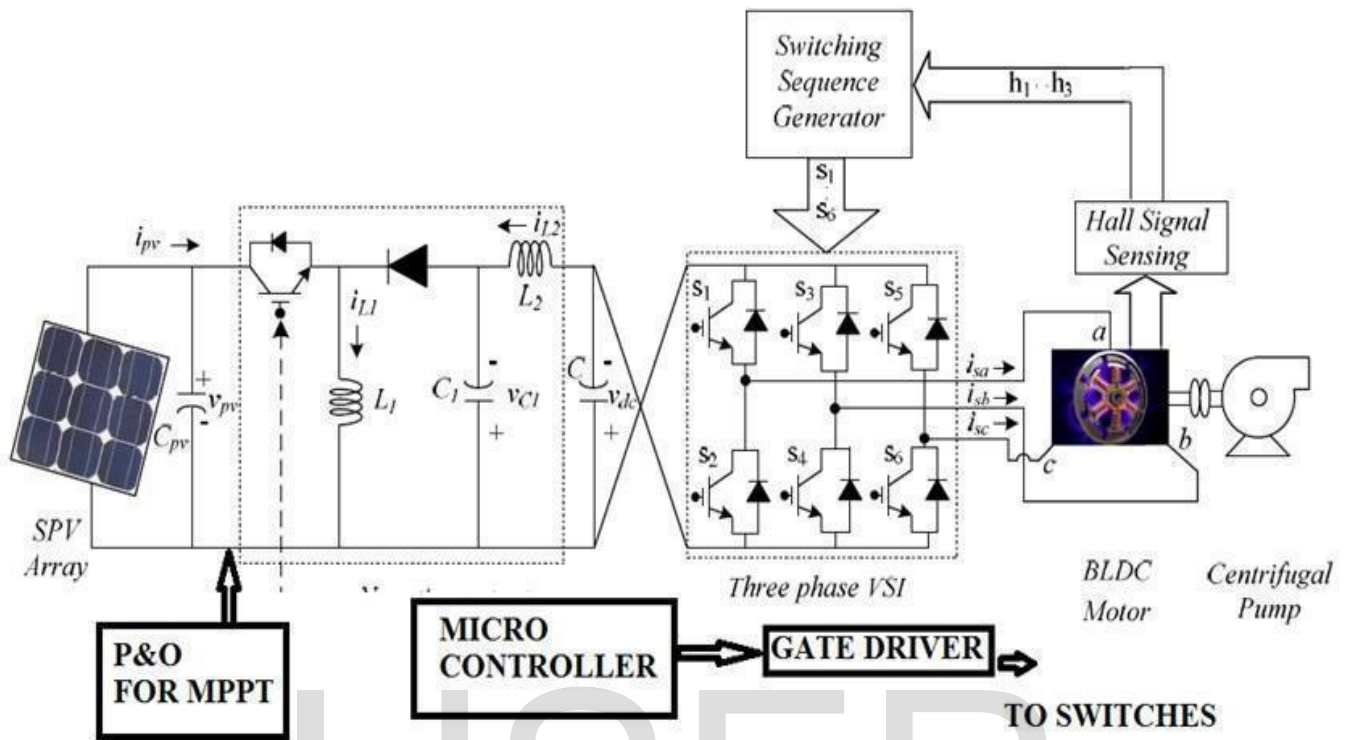

Fig. 1 Configuration of proposed SPV array-Luo converter fed BLDC motor drive for water pumping system.

III. DESIGN OF PROPOSED SYSTEM

Various stages of the proposed system shown in Fig. 1 such as SPV array, Luo converter and motor-pump are designed in view of satisfactory, reliable and efficient performance of the developed system regardless of the operating conditions. Each stage is designed at the standard test conditions (1000 W/m^2, 25°C). First of all, a BLDC motor of 5.18 kW, 3000 rpm @ 310 V DC and then accordingly a SPV array of 6 kW peak power rating, slightly more than required by BLDC motor is selected. SPV array with high power generating capacity is designed considering the practical situations where some amount of generated power is lost at conversion stages and motoring action, affecting the system performances. Design procedure for various stages is illustrated individually as follows.

A. Design of SPV Array

The SPV array with peak power generating capacity of $Pmpp = 6$ kW is designed for proposed water pumping system. SolarWorld make PV module, Sunmodule® *SW 50 Poly RMA* [13] is selected to realise a PV array of appropriate size. Electrical specifications of this module are indicated in Table I. Identification of SPV array voltage at MPP, $Vmpp$ initiates the sizing of SPV array. Belonging to the category of buck boost converter, maximum switch utilization of Luo converter occurs at duty ratio of 0.5 [11]. Therefore, the input and output voltage of Luo converter must be equal to satisfy the aforesaid condition

It is known that the DC voltage rating of BLDC motor or DC link voltage of VSI, Vdc i.e. output voltage of Luo converter is 310 V. Now, to achieve the duty ratio of 0.5 by the MPPT operation at standard test condition and hence the maximum switch utilization of Luo converter, it is mandatory to select $Vmpp$ i.e. input voltage of Luo converter as 310 V. For a 6 kW, 310 V (ratings at MPP) SPV array, current at MPP, $Impp$ is estimated as,

$$Impp = Pmpp/Vmpp = 6000/310 = 19.35 \text{ A} \quad (1)$$

Now, it is straightforward to estimate numbers of modules connected in series/parallel in the desired SPV array. Numbers of series modules are as,

$$Ns = Vmpp/Vm = 310/18.2 = 17 \quad (2)$$

Similarly, numbers of parallel modules are as,

$$Np = Impp/Im = 19.35/2.75 = 7 \quad (3)$$

By connecting 17 modules in series and 7 modules in parallel completes the design steps of SPV array of appropriate size as per the requirement of proposed system. Detailed data of designed SPV array are given in Appendix A.

TABLE I. ELECTRICAL SPECIFICATIONS OF SUNMODUL E $^{®}$ SW 50 POLY RMA SPV MODULE

Peak power, P_m (Watt)	50
Open circuit voltage, V_o (V)	22.1
Short circuit current, I_s (A)	2.95
Voltage at MPP, V_m (V)	18.2
Current at MPP, I_m (A)	2.75
Number of cells connected in series, N_{ss}	36

B. Design of Luo Converter

Maximum switch utilization of Luo converter is already considered while designing the SPV array in previous sub - section. The design of Luo converter includes estimation of input inductor, $L1$, intermediate capacitor, $C1$, output inductor, $L2$ and output capacitor C. These converter elements are estimated with duty ratio, $D = 0.5$ such that Luo converter is always operated in CCM. A high value of switching frequency, $f_{sw} = 20$ kHz is selected in order to get the reduced value of converter elements. The DC link current of VSI i.e. the output current of Luo converter, I_{dc} is equal to I_{mpp} i.e. the input current of Luo converter as the power and voltage level are identical at both the input and output stage of converter.

Input inductor, $L1$ is estimated as [6],

$$L_1 = \frac{DV_{mpp}}{f_{sw} \Delta I_{L1}} = \frac{0.5*310}{20000*(19.35+19.35)*0.04} = 5 \text{ mH} \quad (4)$$

where ΔI_{L1} is amount of ripple permitted in the current flowing through $L1$, addition of input and output current of Luo converter.

Output inductor, $L2$ is estimated as,

$$L_2 = \frac{(1-D)V_{dc}}{f_{sw}\Delta I_{L2}} = \frac{(1-0.5)*310}{20000*19.35*0.08} = 5 \text{ mH} \quad (5)$$

where ΔI_{L2} is amount of ripple permitted in the current flowing through $L2$, equal to the output current of Luo converter [6].

To estimate DC link capacitor, C, the fundamental output voltage frequencies of the VSI corresponding to the rated speed of BLDC motor, ω_{rated} and the minimum speed of BLDC motor essentially required to pump the water ($N = 1100$ rpm), ω_{min} are taken into account which are estimated as,

$$\omega_{rated} = 2\pi f_{rated} = 2\pi \frac{N_{rated}P}{120} = 2\pi*\frac{3000*6}{120} = 942 \text{ rad/sec.} \quad (6)$$

$$\omega_{min} = 2\pi f_{min} = 2\pi \frac{NP}{120} = 2\pi*\frac{1100*6}{120} = 345.57 \text{ rad/sec.} \quad (7)$$

where f_{rated} and f_{min} are the frequencies corresponding to ω_{rated} and ω_{min} respectively, in Hz; N_{rated} is rated speed of BLDC motor; P is the numbers of poles in BLDC motor.

Since 6th harmonic component of ac voltage is reflected from the motor on the DC link of VSI as a dominant harmonic, two values of C are estimated corresponding to ω_{rated} and ω_{min} as,

$$C_{rated} = \frac{I_{dc}}{\omega*V_{dc}} = \frac{19.35}{6*942*310*0.06} = 184 \text{ μF} \quad (8)$$

$$C_{min} = \frac{6*I_{rated}}{6*\omega_{min}*V_{dc}} = \frac{19.35}{6*345.57*310*0.06} = 500 \text{ μF} \quad (9)$$

where ΔV_{dc} is the amount of permitted ripple in the voltage across C.

Finally, $C = C_{min} = 500$ μF is selected as DC link capacitor (larger one out of the two estimated values to ensure satisfactory performance of proposed system irrespective of the operating conditions). Thence, $C1$ is also selected as 500 μF to avoid the oscillations in the various indices of Luo converter [6]. Estimated values of elements of Luo converter are repeated in Appendix B.

C. Design of Centrifugal Water Pump

Design of centrifugal water pump depicts the estimation of proportionality constant, K using the following relationship as [14],

$$K = \frac{T_L}{\omega_r^2} = \frac{16.5}{(2\pi*3000/60)^2} = 1.67*10^{-4} \quad (10)$$

where T_L is equal to the rated torque of BLDC motor, T_{rated} under steady state and ω_r is rated speed of BLDC motor in rad/sec.

This centrifugal water pump is selected for the proposed system and its detailed data are given in Appendix C.

IV. CONTROL OF PROPOSED SYSTEM

The proposed system is required to control at two stages which are explained in brief as follows.

A. Incremental Conductance MPPT

An INC-MPPT technique [2] is used to coerce SPV array to operate at its MPP for each solar insolation level. In reality, the Luo converter is controlled via the execution of INC-MPPT algorithm to reach the MPP of SPV array. Proper selection of perturbation size facilitates reduced current starting of BLDC motor, avoiding the harmful effect of high starting current in motor windings.

B. Electronic Commutation of BLDC Motor

Motor Power Company make TETRA 142TR16.5 BLDC motor [15] is selected for the proposed SPV array fed water pumping system. Electronic commutation of BLDC motor is accomplished by operating three phase VSI in 120° conduction mode using six switching pulses generated according to the rotor position [9]. The inbuilt encoder senses the rotor position on each 60° span, generates a particular set of three Hall effect signals and accordingly the switching sequence for VSI is generated. Fundamental frequency switching of VSI is attained by the electronic commutation of BLDC motor. Detailed data of selected BLDC motor are given in Appendix C.

V. RESULTS AND DISCUSSION

The configuration of proposed SPV array fed water pumping system shown in Fig. 1 is designed, modeled and simulated using MATLAB along with Simulink and its sim-power-system toolboxes. Various starting, dynamic and steady state performances of the system under study subjected to uncertain operating/environmental conditions are illustrated in Figs. 2-4. To demonstrate the dynamic behavior, solar insolation level is considered to be of varying nature as indicated in Table II. Various performances of each stages viz. SPV array, Luo converter and BLDC motor-pump are described separately in following sub-sections.

A. Performance of SPV Array & INC-MPPT Algorithm

Fig. 2 depicts the various SPV array indices viz. solar insolation level, S, SPV array voltage, v_{pv}, SPV array current, i_{pv} and SPV array power, P_{pv}. At the starting, MPPT algorithm takes time to reach the operation of SPV array at MPP under steady state in view of the reduced current starting of BLDC motor. It is clearly visible that the MPPT technique is capable of optimizing the SPV array power under dynamically changing atmospheric condition. Since the proposed system is designed considering the standard value of S, SPV array indices reach their rated value at 1000 W/m^2.

B. Performance of Luo Converter

Various performance indices of Luo converter viz. current flowing through the input inductor, i_{L1}, voltage across the intermediate capacitor, v_{C1}, current flowing through the output inductor, i_{L2} and voltage across the DC link of VSI, v_{dc} are illustrated in Fig. 3. All these indices instantly follow the variation in S. Fig. 3 clearly demonstrates the operation of Luo converter in CCM. High frequency switching avoids the ripple contents in various indices.

TABLE II. VARIATION IN SOLAR INSOLATION LEVEL

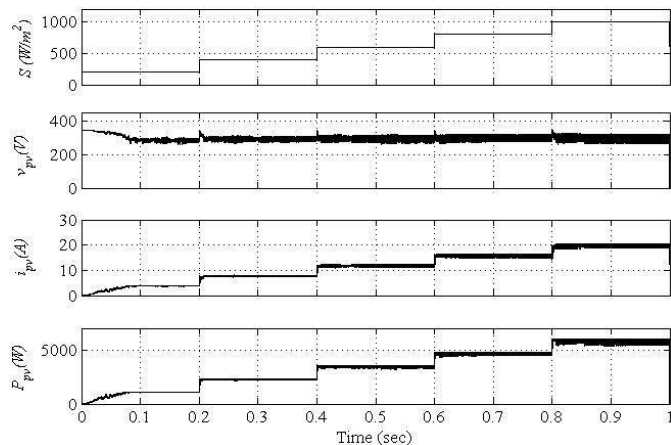| S (W/m^2)	Duration (Sec.)
200	0.0 - 0.2
400	0.2 - 0.4
600	0.4 - 0.6
800	0.6 - 0.8
1000	0.8 - 1.0

Fig. 2 Performances of SPV array of the proposed SPV array - Luo converter fed BLDC motor drive for water pumping system.
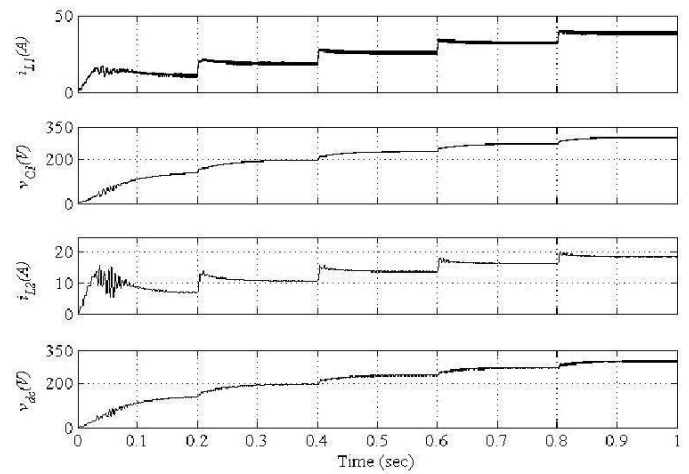

Fig. 3 Performances of Luo converter of the proposed SPV array-Luo converter fed BLDC motor drive for water pumping system.
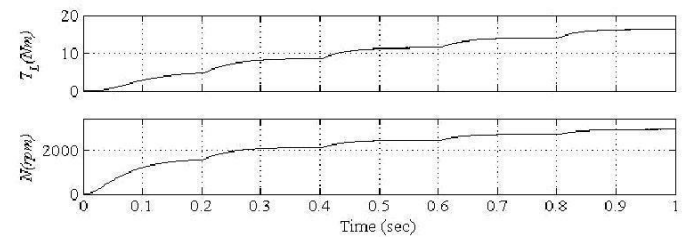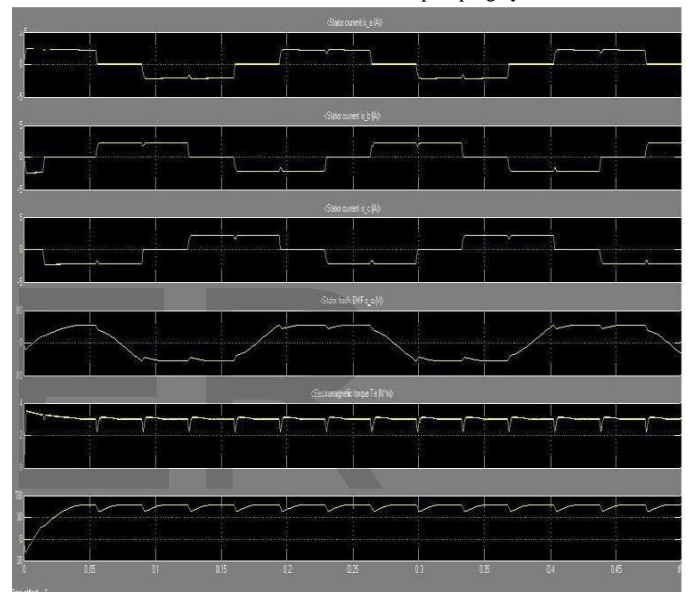

Fig. 4 Performances of BLDC motor-pump of the proposed SPV array-Luo converter fed BLDC motor drive for water pumping system.

C. Performance of BLDC Motor-Pump

Fig. 4 presents the starting, dynamic and steady state performance of BLDC motor -pump system subjected to a rapidly varying solar insolation level. As the DC link voltage varies, various motor-pump indices viz. the back EMF, e_a, the stator current, i_{sa}, the electromagnetic torque, T_e, the pump load torque, T_L and the rotor speed, N vary accordingly. It is clear from the waveform of i_{sa} that the high starting current of

BLDC motor is constrained and its safe starting is achieved. The BLDC motor -pump indices reach their rated values at

1000 W/m^2 under steady state condition. The motor always attains the

speed of more than 1100_2rpm even at the lowest

solar insolation level of 200 W/m . Therefore, the water pumping is not irrupted by the dynamic variation in solar insolation level. Small pulsation in T_e is observed because of electronic commutation of BLDC motor. The pump load

torque, T_L is always balanced by the electromagnetic torque, T_e as an evidence of stable operation of motor-load system.

VI. CONCLUSION

A solar photovoltaic array fed Luo converter based BLDC motor has been proposed to drive water-pumping system. The proposed system has been designed, modeled and simulated using MATLAB along with its Simulink and sim-power-system toolboxes. Simulated results have demonstrated the suitability of proposed water pumping system. SPV array has been properly sized such that system performance is not influenced by the variation in atmospheric conditions and the associated losses and maximum switch utilization of Luo converter is achieved. Luo converter has been operated in CCM in order to reduce the stress on power devices. Operating the VSI in 120° conduction mode with fundamental frequency switching eliminates the losses caused by high frequency switching operation. Stable operation of motor-pump system and safe starting of BLDC motor are other important features of the proposed system.

APPENDIX A

Parameters of solar PV array: Open circuit voltage, V_{oc} = 375.7 V; Short circuit current, I_{sc} = 20.65 A; Maximum power,

P_{mpp}= 6 kW; Voltage at MPP, V_{mpp} = 310 V; Current at MPP, I_{mpp}= 19.35 A; Numbers of cells connected in series in a

module, N_{SS}= 36; Numbers of modules connected in series, N_S = 17;

Numbers of modules connected in parallel, N_p = 7.

APPENDIX B

Parameters for Luo converter: Switching frequency, f_{SW}= 20 kHz; Input

inductor, L_1 = Output inductor, L_2 = 5 mH; Intermediate capacitor, C_1 = DC link Capacitor, C = 500 µF.

APPENDIX C

Parameters for BLDC Motor-Pump: Stator phase/phase

resistance, R_S = 0.41 Ω; Stator phase/phase inductance, L_S= 2. 13 mH; Torque constant, K_t = 0.74 Nm/Apeak; Voltage constant, K_e = 78 VpeakL-L/krpm; Rated current, I_{srated} = 22.15 A; Rated torque, T_{rated} = 16.5 Nm; Rated speed, N_{rated} = 3000 rpm @ 310 V DC; Rated power, P_{rated} =2 5.18 kW; No. of poles, P = 6; Moment of inertia, J = 45.9 kg.c m ;

Proportionality constant, $K = 1.67*10^4$.

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