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Green Electricity Generation: Prospective Analysis on Proposed Padma Bridge, Bangladesh

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Keywords : piezoelectric, PZT, chopper circuit, inverter, MOSFET.

I. Introduction

There is a close relationship between the level of energy consumption in a country and its economic development. The energy consumption in the world has been growing at an alarming rate. The energy crisis is becoming the main problem to mankind facing today due to rapid depletion of non-renewable energy resources like fossil fuels, oils and natural gases [1]. In a third world country like ours, there is always a tug-of-war between limited resources and unlimited public demand.

Despite the audacious effort of our govt. to make Bangladesh a Load-shedding free country, it seems to be a day-dream unless there is some contribution from other innovative sources. Power generators often use fossil fuels like gas, oil which are not unlimited on earth. A recent survey shows that the proven probable natural gas reserves in the country is as much as 28.8567 Trillion Cubic Feet (TCF), although the actual reserve of this most important fossil fuel of Bangladesh has not yet been ascertained [2, 3]. Fuel costs for generators are significant and extreme heat emission and sound pollution from the radiator make the generators environment unfriendly. Again total storage capacity of petroleum products (Diesel, kerosene, petrol and octane) in the country is 687,500 tons which is only 8% of the total demand [4]. But renewable sources like sunlight and piezoelectric material are free as well as unlimited and of course, make environment friendly generation of power. Moreover, less maintenance cost and robustness makes renewable energy the favorite fuel for generation of power.

Piezoelectric materials are a potential source of energy that has never been used in Bangladesh before for power generation. But once implemented properly, it can serve as a perpetual source of energy. This material is gaining an upsurge trend in other country.

II. Piezoelectric Energy

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry. Energy harvesting from piezoelectric elements are becoming popular. Input vibration or pressure causes mechanical strain in the device that is converted to electrical charge.For power generation Lead-zirconate-titanate, commonly known as PZT, is used though there are over 200 piezoelectric materials that could be used for energy harvesting [5, 6]. Figure 1 shows piezoelectric materials.

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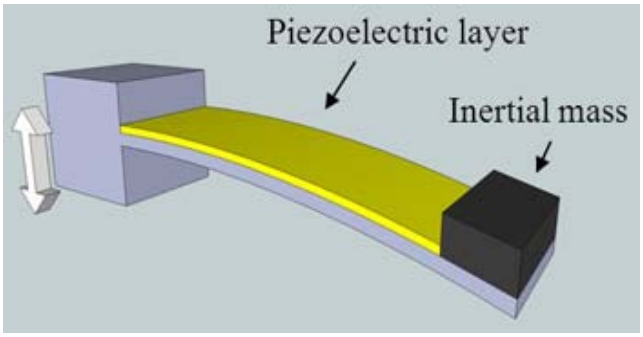

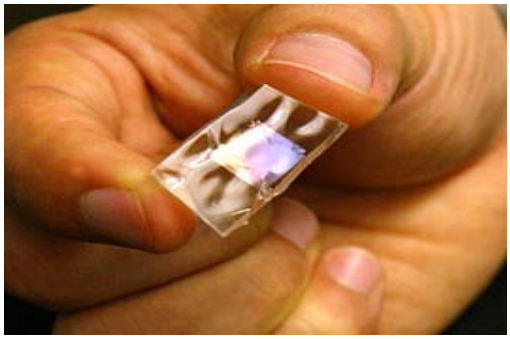

Figure 1 : Piezoelectric Materials[7, 8]

III. Mechanism

The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. Of decisive importance for the piezoelectric effect is the change of polarization P when applying a mechanical stress. This might either be caused by a re-configuration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under the influence of the external stress. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on (a) the orientation of P within the crystal, (b) crystal symmetry and (c) the applied mechanical stress. The change in P appears as a variation of surface charge density upon the crystal faces, i.e. as a variation of the electrical field extending between the faces, since the units of surface charge density and polarization are the same, [C/m^2] = [Cm/m^3]. However, piezoelectricity is not caused by a change in charge density on the surface, but by dipole density in the bulk. For example, a 1 cm^3 cube of quartz with 2 kN of correctly applied force can produce a voltage of 12500 V. The simplest and most compact method of obtaining high voltage from the piezoelectric was to compress it axially. The compression was quasi-static, so that the dynamic mechanical processes need not be considered. [9]

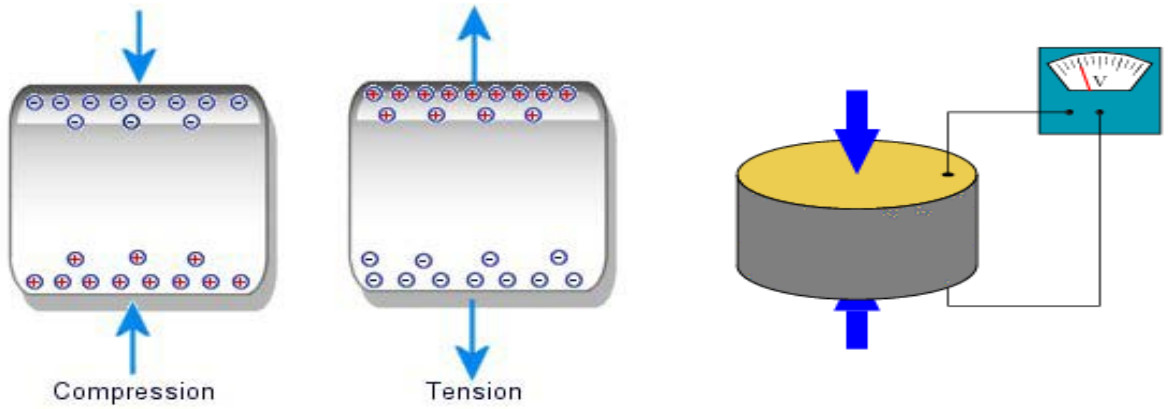

Figure 2 : Charge accumulation in piezoelectric material as pressure is applied externally [10,11]

The constitutive equations are:

$$S_j = s_{kj}^E T_k + d_{im} E_m \quad (1)$$

$$D_i = d_{im} T_m + \epsilon^T E_m \quad (2)$$

Or equivalently:

$$S_j = s_{ki}^D T_k + g_{nj} D_n \quad (3)$$

$$E_n = \beta_{mn}^T D_m - g_{nj} T_j \beta_{mm} = \varepsilon_{mm}^{-1} \quad (4)$$

where s^D is the open-circuit compliance defined by:

$$S^D = S^E - d_{jk} d_{mi} \left(\varepsilon_{mj}^T\right) \quad (5)$$

g is the piezoelectric voltage coupling, d contains the piezoelectric coupling terms which relate the electrical and mechanical properties of the material, S is the strain dimensionless), D is the electric displacement or charge density (C/ m^2), E is the electric field (V/m),and T is the applied stress (N/m^2).

Considering the simple case of a cylindrical piezoelectric element, which is compressed axially in the z-direction, there are two cases of specific interest. The first one is when the electrodes at each end of the element are short-circuited together. In this case, E_3=0 and the charge produced by the piezoelectric element can be calculated readily from Eq. (2)

$$Q = D_3 A = d_{33} T_3 A = d_{33} F \quad (6)$$

Where F is the applied force, A is the cross-sectional area of the element and the subscripts refer to the location in the respective matrices. Note that the

force cannot be increased indefinitely due to a nonlinear piezoelectric effect in the short circuit case, which can lead to irreversible depolarization of the piezoelectric element. This effect occurs when the mechanical stresses in the piezoelectric element are sufficient to cause changes in the ferroelectric domain boundaries. The other case of interest is when the electrodes are open-circuit, so that no charge displacement is possible and $D_3 = 0$. The voltage V developed across the piezoelectric material when the force is applied can be calculated using Eq. (4)

$$V = E_3 l = -g_{33} T_3 l = -g_{33} \frac{Fl}{A} = -\frac{d_{33} F}{C_0} \quad (7)$$

Where C_0 is the capacitance of the unstressed piezoelectric element.From Eq. (4) & (7) the voltage V across the piezoelectric and load capacitances is given by

$$V = E_3 l = -g_{33} T_3 l - \frac{C_L l}{\varepsilon_{33}^T A} V \quad (8)$$

So that

$$V = -\frac{g_{33} T_3 l}{\frac{C_L}{C_0}+1} = \frac{V_{oc}}{\frac{C_L}{C_0}+1} \quad (9)$$

Where V_{OC} is the open-circuit voltage that would have been obtained without the load. The efficiency, η with which the piezoelectric energy is transferred to the load is given by

$$\eta = \frac{\frac{1}{2} C_L V^2}{\frac{1}{2} C_0 V_{oc}^2} = \frac{\frac{C_L}{C_o}}{\left(\frac{C_L}{C_o}+1\right)^2} \quad (10)$$

Equation (10) is shown graphically in Fig. 3. The maximum charging efficiency is 25 % and occurs when the load and piezoelectric capacitances are equal.
The equivalent circuit for piezoelectric generator is

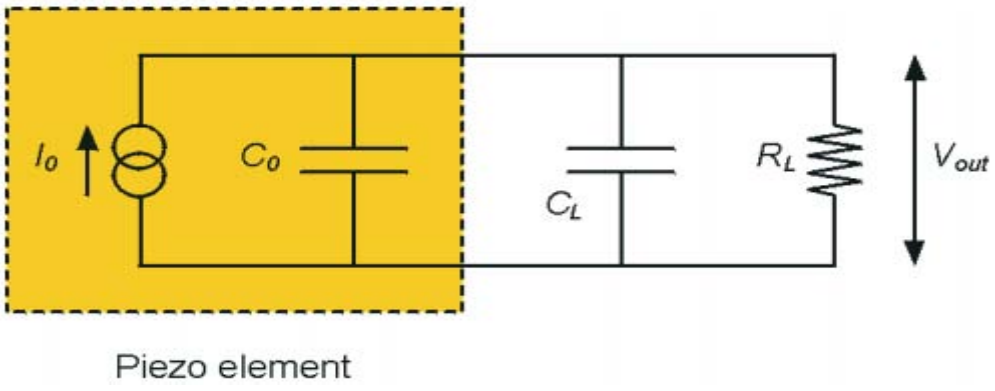

Figure 3 : Equivalent circuit of piezoelectric material when stressed

IV. Proposed Project

The following diagram shows the proposed plan for power generation from Padma Bridge which can also be utilized in any bridge or road side for green electricity generation.

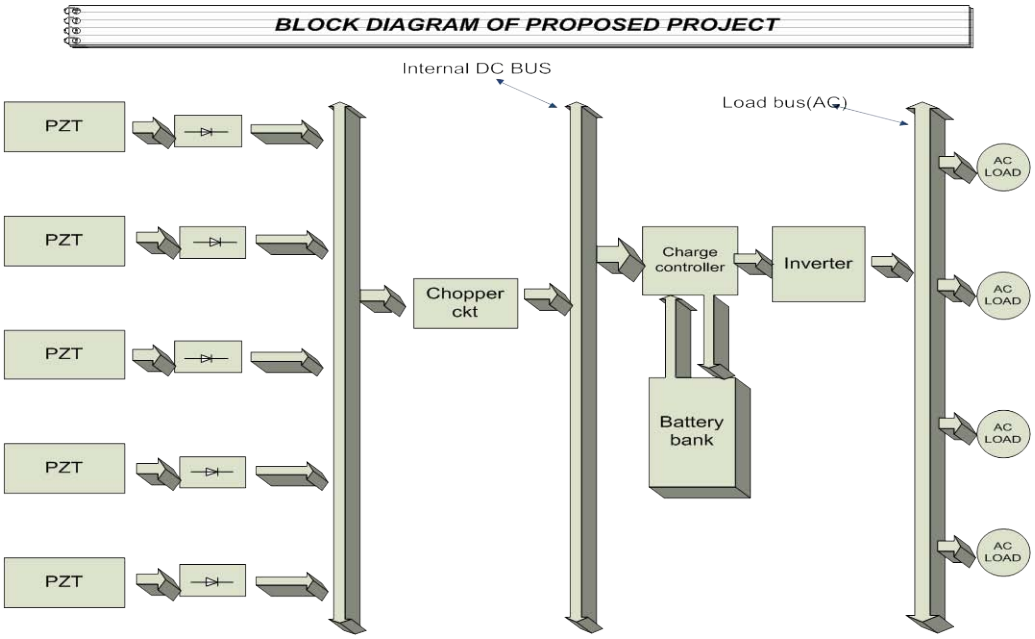

Figure 4 : Proposed Plan

a) Required Materials

In this scheme of power generation required materials are; PZT Pad, chopper circuit, battery bank, charge controller and inverter.

i. *PZT pad*

PZT pad will be installed within the road track under the pitch layer. When the vehicles run over the PZT pad, it will extract the mechanical energy and convert it into usable electrical energy. The vehicles pressure deforms the piezoelectric materials and providing a small amount of electrical charge. This pad is actually capturing wasted energy, energy that was previously just heat lost.

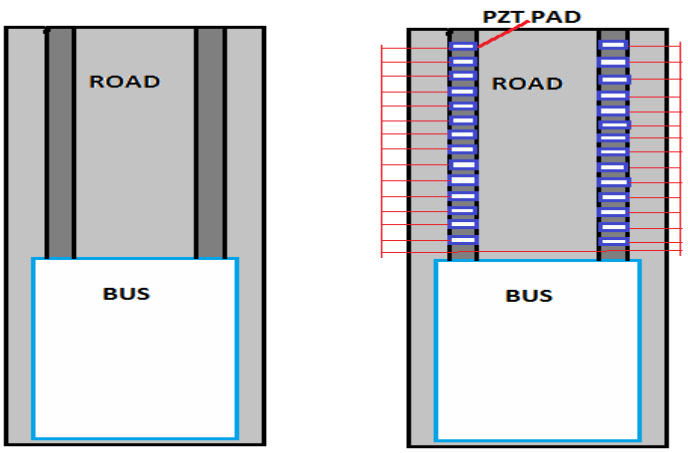

Figure 5 : PZT pad

ii. *Chopper Circuit*

Chopper circuit is commonly known as DC to DC converter circuit. At the terminals of the PZT pads, very high voltage up to 150kV is generated. It is difficult to work with and store energy at this high voltage. That is why we need to lower the high DC voltage to a value at which the energy generated can be stored at the battery bank. For this reason, chopper circuit is needed.[12]. A simplified chopper circuit is:

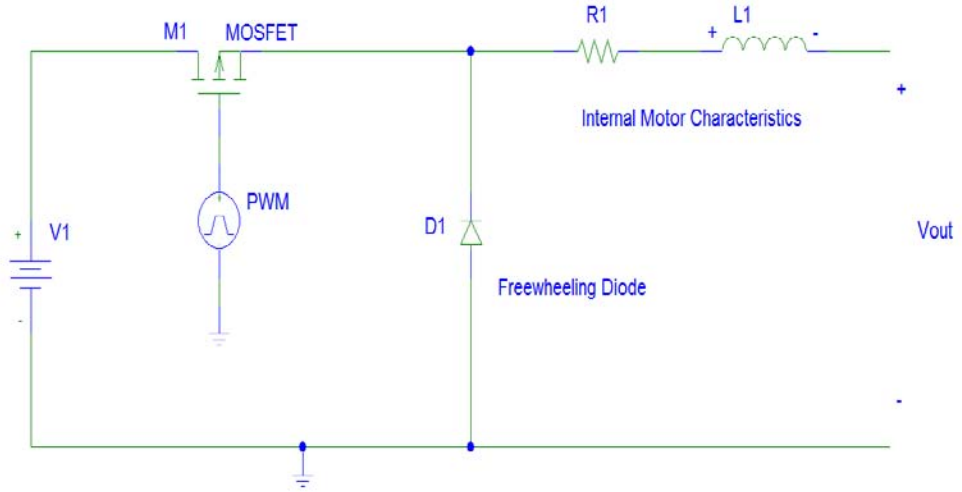

Figure 6 : Simplified chopper circuit

iii. *Battery Bank*

Battery bank is an important component of our power scheme. The power scheme does not always generate energy. Sometimes it generates excess energy and sometimes it does not energy at all. To deliver energy to the load all the time and to utilize the excess energy, battery bank is a must. It doesn't matter how much power we generate - if it is not stored safely and efficiently then we will have no electricity when we need it.

Figure 7 : Practical battery bank [13]

iv. *Charge Controller*

Charge Controller is needed to prevent overcharging of the batteries. Proper charging will prevent damage and increase the life and performance of the batteries. In this power scheme, charge controller is used to control the flow of energy. When piezoelectric materials are generating energy, charge controller connects the battery bank with the piezoelectric materials and battery is charged. The battery bank also delivers energy to the load through charge controller. We have used PWM type charge-controller to reduce the controller cost.

The rating of charge controller used in this proposed project is 48V as the battery is charging at that voltage.

v. *Inverter*

The inverter is one of the most important and most complex components of an independent system. The inverter converts DC to AC, and also changes the voltage. In other words, it is a power adapter. DC flows in a single direction. AC alternates its direction many times per second. [14].The standard DC voltages for home- size systems are 12, 24 and 48 volts. The standard for AC utility service in USA is 120 and 240 volts at 60 Hertz (cycles per second). In Europe and some countries in Latin America, Asia and Africa, it's 220V at 50 Hertz.

Here the power scheme is to produce 220VAC at 50Hz from 48V. Inverter is selected with such rating.

V. Power Calculation

Each of the PZT pad will eventually face the force of the whole Bus. So the approximated force on each PZT pad is equal to the weight of the vehicle.

Approximate weight of medium size vehicle is 5 Ton. And each boggy has four wheel. So, weight on each wheel, F = 1.25Ton =1.25*9.8=12.25 kN.

For PZT, $d_{33}=390*10^{-12}$ C/N.

So, Charge accumulated in one PZT unit = d_{33}* F= 4.778μC.

Due to depolarization effect of the piezoelectric material, the charge accumulation exceeds the theoretical value and becomes =5μC.

This charge is accumulated in one PZT crystal with 15mm diameter and 20mm length.

So, no of PZT crystals in one PZT pad = 100 unit

Charge accumulated = 100*5 = 0.5mC

If we install PZT pad on every 1m, then total number of PZT pads are installed in 6150m (length of proposed Padma bridge) in one lane = 2*6150 = 12300

There are four lane so total number of PZT pads = 12300*4 = 49200

So total charge accumulated when one vehicle passes, Q = 49200*0.5mC = 24.6C

Now, the intrinsic capacitance of one PZT unit = 135pF

So, total intrinsic capacitance for one PZT pad = 13.5nF

For stability of the system, capacitor equal magnitude of total intrinsic capacitance is connected parallel with the PZT pad.

So, the output voltage becomes, V = 37.04kV. [From Eq. 9]

Energy generated for one vehicle = V*Q = 911.18 kJ = 0.253kWh

Let a Padma bridge receives 16272 vehicles a day in 2018 [15]. So per hour 678 vehicles

Then the energy generated in one day is = 171.534 kWh.

Let the efficiency of Chopper Circuit = 0.9

Efficiency of charge controller = 0.9

Efficiency of Inverter = 0.94

So output energy = 0.9*0.9*0.94*171.534 = 130.606 kWh

VI. Conclusion

The main purpose of the proposed project is to generate piezoelectricity from highway road to supply its own electricity demand. As an example, proposed Padma bridge is taken. The sufficient calculation shows that this is an effective way to produce electricity through the road vehicles movement to support the bridge own electricity demand. All the calculations are considered for the Proposed Padma Bridge in Bangladesh. Although this project is costly but at the long run it is fruitful. This project can be implemented at any road side too. In Bangladesh, there is a total 21,481.25 Km road including national and regional highway and Zilla road. Huge number of bridges and culverts are also available amounting 18258 [16]. This project can effectively also be utilized in railway track as Bangladesh railway covers a length of 2855 km including 3650 bridges. [17]

Again further development can be made as hybrid power generation. This piezoelectricity along with solar cell or wind can be utilized as electricity source for large power generation.

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